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14. ABSTRACT
In this project, we developed methods for adaptive design of signals transmitted by radar or communication systems. The proposed methods optimize the performance in the presence of time-varying environmental conditions and, in the case of radar, respond to unknown parameters of static and dynamic targets. We devised algorithms that exploit the waveform diversities in multiple dimensions, such as time, space, frequency, phase, power, and polarization. We demonstrated thorough analysis and numerical examples that our proposed methods provide dramatically improved performance over existing systems. We considered various aspects, including waveform design, environment modeling, algorithms for target detection and tracking, waveform adaptivity in communications, compressive sensing and through-the-wall radar. Our contributions reflect the multidisciplinary subjects of the project and composition of our team of experts in mathematics, statistics, engineering, and physics.

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MURI: Adaptive Waveform Design for Full Spectral Dominance (2005-2010)

AFOSR FA9550-05-1-0443

Final Report

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Overview

In this project, we developed methods for adaptive design of signals transmitted by radar or communication systems. Such methods are aimed to optimize the performance in the presence of time-varying environmental conditions and, in the case of radar, respond to unknown parameters of static and dynamic targets. We devised algorithms that exploit the waveform diversities in multiple dimensions, such as time, space, frequency, phase, power, and polarization. We demonstrated, thorough analysis, that our proposed methods provide dramatically improved performance over existing systems.

We considered various aspects, including waveform design, environment modeling, algorithms for target detection and tracking, waveform adaptivity in communications, compressive sensing and through-the-wall radar. Our contributions reflect the multidisciplinary subjects of the project and composition of our team. Namely, we had experts in mathematics, statistics, engineering, and physics. The research of the team members span the areas of signal processing, radar, electromagnetics, information theory and communications. We summarize in the following links and files more details of our achievements.

- **Website: http://signal.ese.wustl.edu/MURI/index.html**
- **2006 Annual Report**
- **2007 Annual Report (Version 1)**
- **2007 Annual Report (Version 2)**
- **2008 Annual Report**
- **2009 Annual Report**
- **2010 Annual Report**
- **Summary of MURI topics from 2009-1010**
- **Summary of MURI statistics**

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Annual Report
Research Under MURI AFOSR Grant FA9550-05-1-0443
“Adaptive Waveform Design for Full Spectral Dominance”
Period 1: July 2005 to February 2006

Arye Nehorai
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INTRODUCTION

In the following we summarize the contributions we made under MURI AFOSR Grant FA9550-05-1-0443 “Adaptive Waveform Design for Full Spectral Dominance” during Period 1, from July 2005 to February 2006.

WAVEFORM DIVERSITIES

Polarimetric Signals

In [1], we describe a simple diversity technique with the potential to improve detection performance of any conventional polarimetric radar and with the advantage that signal processing complexity is essentially the same as for the base-line radar system. The advantage of polarization diversity over spatial diversity is that time-synchronization of the vertical and horizontal returns from a target is automatic, so that the complications of time-of-arrival signal processing are avoided. Golay pairs of phase-coded waveforms are used to provide receiver synchronization and enable the use of the Alamouti signal processing to estimate polarimetric properties of the target.

Time-varying Signals

The advent of waveform-agile sensors has enabled the design of tracking systems where the transmitted waveform is changed on-the-fly in response to the tracker's requirements. This approach can provide performance improvements over individual optimization of the sensor waveform or the tracking algorithm. In [2], we consider joint sensor configuration and tracking for the problem of tracking a single target in the presence of clutter using range and range-rate measurements obtained by waveform-agile, active sensors in a narrowband environment. We propose an algorithm to select and configure linear and nonlinear frequency-modulated waveforms to minimize the predicted mean square error (MSE) in the target state estimate; the MSE is predicted using the Cramér-Rao lower bound on the measurement error in conjunction with the unscented transform. We further extend our algorithm to match wideband environments, and we demonstrate the algorithm performance through a Monte Carlo simulation of a radar tracking example.

Frequency-coded Sequence

In [3], we develop frequency-coded sequences for adaptive waveform radar (this work is still in progress).

Space-Time Coding

In [4], we derive a hybrid of Beamforming (BF) and Space-Time Block Coding, where the space-time code is transmitted over the beams generated by the steering vectors corresponding to the channel path directions. This is for the practical case where the transmit array may have reliable information on the departure angles of the dominant paths between transmitter and receiver, but no knowledge of the associated complex path gains. We compute analytically the SNR of the proposed hybrid scheme for the specific case of a two-path channel model with Alamouti encoding of the attendant beams, and compare the result to the SNR of beamforming with perfect knowledge and the theoretically possible SNR of an Orthogonal Space-Time Block

Code (STBC). Simulation results show that the performance of the proposed BF/STBC hybrid is very close to that of ideal BF with perfect and full channel knowledge under certain conditions. In the practical case where there is phase estimation error in the complex path gain estimates, the simulations reveal the proposed BF/STBC hybrid to perform substantially better than beamforming, with the latter experiencing a huge performance loss due mismatch.

Multicasting is the general method of conveying the same information to multiple users. For multicasting applications over multiple-input multiple-output (MIMO) channels, it is of great importance to ensure that all users experience an adequate level of performance while utilizing the transmit diversity available in MIMO channels. One technique, called max-min beamforming, provides a way to increase the received signal-to-noise ratio (SNR) of the worst-case user. However, due to its limited degrees of freedom, this method suffers severe performance degradation when the number of users increases. Alternatively space-time codes can be employed to transmit data simultaneously to all users. In [5], we introduce additional degrees of freedom in the time domain, open-loop orthogonal space-time block coding (OSTBC) schemes, and achieve better performance than max-min beamforming when the number of users is large. In this paper, a precoded OSTBC scheme is proposed that optimizes the performance of the worst-case user. By pre-multiplying the OSTBC codeword by a precoding matrix, the transmitter can adapt to current channel conditions which results in a higher worst-case receive SNR. Simulation results demonstrate that the proposed scheme performs universally better than open-loop OSTBC schemes and outperforms the max-min beamforming scheme for a large number of users.

Zero-autocorrelation Waveforms

Constant amplitude zero autocorrelation (off the dc component) waveforms are constructed in [6]. These are called CAZAC waveforms. In the d-dimensional case they consist of N vectors, where N is given, and N is generally greater than d. The constructions are algebraic and have been implemented in user friendly software. They have the added feature that they are a spanning set for all d-dimensional signals. As such, and for N large, they are numerically stable in the presence of machine imperfections and they give good signal reconstruction in the presence of various noises. The one dimensional case provides effective thresholding to compute Doppler shifts.

There are several natural constructions of constant amplitude zero autocorrelation (off the dc-component) waveforms. In [7], we adopt a construction for waveforms of length K, where K is a non-square-free integer. This property of K is necessary for the derivation of a frequency shifting (Doppler) detection algorithm which we derive. There are number theoretic properties which account for the effectiveness of the algorithm. A variety of relevant examples is given along with the technical rationale for the algorithm.

Waveform Library Generation

In [8], we provide a new way of understanding Golay pairs (of length N) of sequences in terms of the $(2N + 1)$-dimensional discrete Heisenberg-Weyl group over the field Z2. Our methodology provides a different insight into the nature of these sequences, as well as a mechanism for designing sequences with desirable correlation properties. Libraries of waveforms formed using these constructions are able to provide collections of ambiguity functions that cover the range-Doppler plane in an efficient way, and thus provide the basis for a suite of waveforms optimized for extraction of information from the environment in an active sensing context.

In [9], we extend the idea of adaptive waveform selection for radar target tracking to interacting multiple model (IMM) trackers to permit the modeling of maneuvering targets by allowing multiple possible dynamical models. We develop a one step ahead solution to the problem of waveform selection, which is designed to decrease dynamic model uncertainty for the target of interest. It is based on maximization of the expected information obtained about the dynamical model of the target from the next measurement. We also discuss the design of waveform libraries for target tracking applications.

ENVIRONMENT AND CHANNEL MODELING

Polarimetric Target and Multipath Channel

We consider the problem of passive localization of a low-grazing-angle source employing polarization sensitive sensor arrays in [10]. We present a general polarimetric signal model that takes into account the direct field and the multipath interference produced by reflections from smooth and rough surfaces. Applying the Cramér-Rao bound (CRB) and mean-square angular error (MSAE) bound, we analyze the performance of different array configurations, which include an electromagnetic vector sensor (EMVS), a distributed electromagnetic component array (DEMCA), and a distributed electric dipole array (DEDA). By computing these bounds, we show significant advantages in using the proposed diversely polarized arrays compared with the conventional scalar-sensor arrays.

Time-varying and Dispersive Channel

Time-varying systems can be characterized by dispersive signal transformations such as nonlinear shifts in the phase of the propagating signal, causing different frequencies to be shifted in time by different amounts. In [11, 12], we propose a discrete time-frequency model to decompose the dispersive system output into discrete dispersive frequency shifts and generalized time shifts, weighted by a smoothed and sampled version of the dispersive spreading function. The discretization formulation is obtained from the discrete narrowband system model through a unitary warping relation between the narrowband and dispersive spreading functions. This warping relation depends on the nonlinear phase transformations induced by the dispersive system. In order to demonstrate the effectiveness of the proposed discrete characterization, we investigate acoustic transmission over shallow water acoustic environments that suffers from severe degradations as a result of modal frequency dispersions and multipath fading. Using numerical results, we demonstrate that the discrete dispersive model can lead to a joint multipath-dispersion diversity that we achieve by property designing the transmitted waveform and the reception scheme to match the dispersive environment characteristics.

In [13], we investigate the dispersive characterization of shallow water environments for acoustic transmissions, and we develop a time-varying system representation to model its dispersive propagation characteristics. We also obtain the discrete model of this representation using a transform-based approach or by nonlinearly warping the discrete time-frequency model of narrowband environments. Using this discrete model in a shallow water communication application, we design a wideband time-varying waveform to match the dispersive nature of the environment. As we demonstrate with numerical results, the design can provide dispersive Doppler diversity by employing maximal ratio combining techniques.

Stochastic Clutter Model

Compound-Gaussian models are used in radar signal processing to describe heavy-tailed clutter distributions. The important problems in compound-Gaussian clutter modeling are choosing the texture distribution, and estimating its parameters. Many texture distributions have been studied, and their parameters are typically estimated using statistically suboptimal approaches. In [14]-[16], we develop ML methods for jointly estimating the target and clutter parameters in compound-Gaussian clutter using radar array measurements. In particular, we estimate (i) the complex target amplitudes, (ii) a spatial and temporal covariance matrix of the speckle component, and (iii) texture distribution parameters. Parameter-expanded expectation-maximization (PX-EM) algorithms are developed to compute the ML estimates of the unknown parameters. We also derived the CRBs and related bounds for these parameters. We first derive general CRB expressions under an arbitrary texture model then simplify them for specific texture distributions. We consider the widely used gamma texture model, and propose an inverse-gamma texture model, leading to a complex multivariate t clutter distribution and closed-form expressions of the CRB. We study the performance of the proposed methods via numerical simulations.

In [17], we develop ML and method of fractional moments (MoFM) estimates to find these distribution parameters. We compute the CRBs on the estimate variances and present numerical examples. We also show examples demonstrating the applicability of our methods to real lake-clutter data. Our results illustrate that, as expected, ML estimates are asymptotically efficient, and also that the real lake-clutter data can be very well modeled by the inverse gamma distributed texture compound-Gaussian model.

Models in Communication System

Outdoor channels can be modeled as a sum of array response vectors of varying gain at different Angles of Departures (AoDs) from different point sources. Based on these characteristics, we derive a hybrid of Beamforming (BF) and Space-Time Block Coding, where the space-time code is transmitted over the beams generated by the array response vectors corresponding to Angles of Departure [18]. This is for the practical case where the transmit array may have reliable information on the departure angles of the dominant paths between transmitter and receiver, but no knowledge of the associated complex path gains. We compute analytically the SNR of the proposed hybrid scheme for the specific case of a two-path channel model with Alamouti encoding of the attendant beams, and compare the result to the SNR of beamforming with perfect knowledge and the theoretically possible SNR of an Orthogonal Space-Time Block Code (STBC). Simulation results show that the performance of the proposed BF/STBC hybrid is very close to that of ideal BF with perfect and full channel knowledge under certain conditions. In the practical case where there is phase estimation error in the complex path gain estimates, the simulations reveal the proposed BF/STBC hybrid to perform substantially better than beamforming, with the latter experiencing a huge performance loss due mismatch.

OPTIMIZATION

Communication Cost Function

In [19], we consider the case of covariance feedback in MIMO communications, where the channel matrix is modeled as a Gaussian random matrix with zero mean and a non-white covariance matrix available at the transmitter through receiver feedback. Although the structure of the optimal input covariance matrix that achieves the ergodic capacity is known, a closed form expression for its eigenvalues is unavailable. In this paper, we propose a water-filling scheme to approximate the capacity-achieving input covariance matrix. Compared to prior work, our proposed solution has the advantage of a simple closed-form expression that makes it easy to implement. We further propose a precoding scheme based on this suboptimal input covariance matrix. Simulation results suggest that under realistic conditions, this precoding scheme offers a 3 to 5 dB improvement when it is combined with either OSTBC or a spatial multiplexing scheme.

Waveform Scheduling

In [20], we consider the problem of scheduling the waveform transmitted by waveform-agile radar sensors to track multiple targets in clutter. A number of generalized frequency modulated chirps with trapezoidal envelope form the library of waveforms available to the sensors, which obtain measurements using a nonlinear observation model. A joint probabilistic data association filter is used to track the target and the waveform selection is made so as to minimize the predicted mean square tracking error. We provide simulation results to show that the scheduling improves the tracking and localization performance.

Tracking Error Minimization

The time-variation due to Doppler scaling effects, coupled with scattering due to multipath propagation, can severely limit the performance of wideband systems. In [21], we examine the dynamic configuration of transmitted waveforms for agile sensing to increase tracking performance in wideband environments. Using wideband frequency modulated waveforms, we present an algorithm for predicting the mean square tracking error and selecting the waveform that minimizes it in a target tracking application with a nonlinear observations model. The algorithm is based on the Cramér-Rao lower bound on the measurement errors that is computed using the wideband ambiguity function. Using simulations, we demonstrate the improved performance provided by scheduling over fixed configurations.

In [22], we consider the problem of dynamic selection of frequency modulated waveforms and their parameters for use in agile sensing. The waveform selection is driven by a tracker that uses probabilistic data association to track a single target in clutter, employing measurements derived from a nonlinear observations model. We present an algorithm that performs the selection so as to minimize the predicted mean square error which is computed using the unscented transform. We compare and analyze the performance of several trapezoidal envelope frequency modulated waveforms with different time-frequency structures using the Cramér-Rao lower bound. The simulation results indicate that the dynamic selection of waveforms and their corresponding parameters improves the tracking performance.

Waveform and Sensor Management

Finding probe signals (pulse sequences) that can compensate for the dispersion in the parameters governing the evolution of a quantum system is an important problem in coherent spectroscopy and quantum information processing. The use of composite pulses for compensating dispersion in system dynamics is widely known and applied. In [23], we make explicit the key aspects of the dynamics that makes such a compensation possible. We highlight the role of Lie algebras and non-commutativity in the design of a compensating probe signal. Finally we investigate three common dispersions in NMR spectroscopy, the Larmor dispersion, rf-inhomogeneity and strength of couplings between the spins.

The efficiency of dipole-dipole coupling driven coherence transfer experiments in solid-state NMR spectroscopy of powder samples is limited by dispersion of the orientation of the internuclear vectors relative to the external magnetic field. In [24], we introduce general design principles and resulting pulse sequences that approach full polarization transfer efficiency for all crystallite orientations in a powder in magic-angle-spinning experiments. The methods compensate for the defocusing of coherence due to orientation dependent dipolar coupling interactions and inhomogeneous radio-frequency fields. The compensation scheme is very simple to implement as a scaffold (comb) of compensating pulses in which the pulse sequence to be improved may be inserted. The degree of compensation can be adjusted and should be balanced as a compromise between efficiency and length of the overall pulse sequence. We show by numerical and experimental data that the presented compensation protocol significantly improves the efficiency of known dipolar recoupling solid-state NMR experiment.

APPLICATIONS AND VALIDATIONS

Multi-target Estimation

Waveform design in real time for radar applications is a challenging task, particularly for estimating multiple targets. In [25], we extend the information theoretic design approach of Bell to multiple targets. We show that under certain simplifying assumptions, the problem can be reduced to solving a convex optimization. We then employ a duality theory method to provide a computationally efficient solution of the problem.

Analytical Studies to Model the Propagation of Electromagnetic Waves Using Ray-tracing Methods

One advantage of ray-tracing methods is that they allow for a direct physical interpretation of the propagation as a superposition of many waves associated with different trajectories. In the frequency domain, ray-tracing methods are well established, even though there is still room for improvements. One recent improvement is the Incremental Theory of Diffraction (ITD). We developed the experiments to compare the prediction obtained with the ITD with our measurements in our anechoic room [26].

Ray tracing methods are also used in the time-domain. In this case, the use of asymptotic theories provides results that are only valid for early times beyond the arrival of the wavefront. The main reason for the limitation to early times is that asymptotic theories neglect the low frequency components of the spectrum associated with the pertinent transfer functions. One may argue that for signals that are ultra-wideband (UWB), according to the Federal Communications Commission definition, the limitation to early times may be relaxed because UWB signals are limited to the frequency interval 3.1 GHz-10.6 GHz. Therefore, there are no low-frequency components to consider and the theoretical predictions may improve [27].

Experiment Validation for Advanced Waveform Design

In [28], we propose to develop experiments to assess the improvements in accuracy of direction of arrival estimation using Rajopalan and Lazzi's antenna, versus the use of scalar array antennas. Experiments will consist in anechoic room measurements of the field received from a source located at a known position.

Repository for Radar Data Files

This project will eventually have hundreds of data files, each of considerable size. Each experimenter will want some but not all of them. They are large enough that downloading all of them is an ill-advised waste of space and bandwidth. The library will evolve over time as new data arrive, as new descriptions of the data emerge, and as new requirements arise. It cannot be completely organized before we start building it and using it. We want to share these files, record how and why they were recorded, retrieve them, and process them - all with consistency, security (free from unauthorized access), safety (without danger of loss), convenience, repeatability, with a common descriptive model, and with timely updating of data for everyone's shared use. We are building a database system to service these requirements.

We envision a central database with data files and metadata describing the data files. The data files will be collected over time and will have numerous parameters describing how and why the data was collected; they may also have differing formats. An initial list of fields has been circulated. The descriptors will be documented in a central easily-accessible place where everyone (and everyone's computer) can read them. We will build a simple browsing system to make it easy to view, search, and retrieve data according to many different characteristics. A central server will retain all the data, but each user runs research experiments on a local machine and usually wants to have a local mirror of the central file. We will provide a method of copying these data files to the user's machine, and maintaining the connection between signal files and their metadata. Also, the tool will ensure consistent naming between users. The user usually wants to create his own view of this data by organizing it and naming it according to his experimental purposes. Supporting this process will provide data integrity and help track the history of experiments conducted. To make the user's programs easier to write, we propose that the metadata not be in the raw data file, but be kept nearby (perhaps in a similarly-named file in the same directory as the data file) and handled by a Java class with an API for a user to request data without the user worrying about the file's format or name or location.

The progress of the database design is listed as below:

- The repository has been through one design cycle.
- An initial design proposal based solely on a web server was circulated November 10, 2005.
- That proposal has been 70% built and installed on a server in Princeton.
- It has demonstrated the uploading of toy data files and associated metadata, and the searching and display of files selected by flexible user specifications.
- It has been shown in Princeton and at the meeting in Maryland on February 2, 2006.
- There has been solid interest, understanding, and requests for changes from users.
- One request (from multiple people) will entail major design changes.
- Said design changes will enable significant additional functionality.

- Work on the revamping has started.
- One sample file in the expected format has been obtained from the collection site.

TEAM ACTIVITIES

Special IEEE Conference Sessions

- A. Papandreou-Suppappola and D. Morrell, organizers of special session on "Advances in Waveform Agile Sensor Processing," *IEEE International Conference on Acoustics, Speech, and Signal Processing*, Philadelphia, PA, March 2005.
- A. Nehorai, organizer of special session on "Signal Processing for Waveform Diversity and Design," *International Waveform Diversity and Design Conference*, Lihue Hawaii, January 2006.
- A. Nehorai, organizer of special session on "Waveform Adaptive Sensing," *Conference on Information Sciences and Systems*, Princeton, NJ, March 2006.
- R. Rangaswamy and A. Nehorai, organizers of special session on "Waveform Diverse Sensors and Systems," *IEEE International Conference on Acoustics, Speech, and Signal Processing*, Toulouse, France, May 2006.

Proposed IEEE Journal Special Issues

- A. Nehorai, A. Papandreou and M. Rangaswamy (guest editors), special issue on Adaptive Waveform Design for Agile Sensing for the *IEEE Journal on Special Topics in Signal Processing*, with February 2007 tentative publication date.
- A. Papandreou-Suppappola, A. Nehorai and D. Cochran (guest editors), special issue on Waveform-Agile Sensing and Processing for the *IEEE Signal Processing Magazine*, with May 2007 tentative publication date.

Meetings Between MURI Team Members

- Sensor, Signal and Information Processing Workshop, Tempe AZ, April 28-29, 2005 (`http://enpub.fulton.asu.edu/sensip/workshop.htm`), A. Nehorai, A. Papandreou-Suppappola, D. Morrell, and M. Rangaswamy.
- Sensor, Signal and Information Processing Seminar, Tempe AZ, December 12-16, 2005 A. Papandreou-Suppappola, D. Morrell, W. Moran and D. Cochran (discussions for collaboration on sea clutter modeling).
- International Waveform Diversity and Design Conference, Lihue Hawaii, January 2006, A. Nehorai, A. Papandreou-Suppappola, M. Rangaswamy, W. Moran, S. Howard, and R. Calderbank.
- Information Theory Workshop, Melbourne, Australia, September 2005, R. Calderbank, W. Moran and S. Howard.
- Princeton University, October 21-26 and December 17-20, 2005, R. Calderbank and W. Moran.
- University of Maryland, February 2, 2006, J. Benedetto, W. Moran and S. Howard.

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MURI: Adaptive Waveform Design for Full Spectral Dominance

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Progress Report - Summary

Sep. 2006 – Feb. 2007

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1 Research

1.1 Waveform Diversities and Design

Periodic Constant Amplitude Zero Autocorrelation (CAZAC) waveforms u are analyzed in terms of the discrete periodic ambiguity function A_u in [1]. Elementary number theoretic considerations illustrate that peaks in A_u are not stable under small perturbations in its domain. Further, it is proved that the analysis of vector-valued CAZAC waveforms depends on methods from the theory of frames. Finally, techniques are introduced to characterize the structure of A_u, to compute u in terms of A_u, and to evaluate MSE for CAZAC waveforms.

CAZAC (Constant Amplitude Zero Auto-Correlation) sequences are important in waveform design because of their optimal transmission efficiency and tight time localization properties. Certain classes of CAZAC sequences have been used in Radar processing for many years while recently discovered sequences invite further study. In [2], we compare several classes of CAZAC sequences with respect to both the periodic and aperiodic ambiguity function. Some computational results for different CAZAC classes are presented. In particular, we note the fact that so-called Björck CAZACs have sidelobes at different locations when different shifts are considered. We took advantage of this fact by using an averaging technique to lower sidelobe levels.

Although no complete characterization of all CAZAC sequences exists, known examples can be classified broadly into two distinct categories. The Frank–Zadoff–Chu codes and their quadratic phase generalizations produce codes with good peak sidelobe levels (PSL) and merit factors (MF), but their ambiguity functions exhibit strong coupling in the time–frequency plane. The quadratic residue sequences of Björck, also called small alphabet CAZACs, can more effectively decouple the effect of time and frequency shifts. However, in terms of PSL and MF, they are not as desirable as Wiener CAZACs. In [3], we show that concatenating Wiener and Björck sequences leads to codes with improved ambiguity functions. These hybrid codes have similar or better PSL and MF compared to the original sequences used to construct them. In addition, we demonstrate that the hybrid ambiguity function remains close to the thumbtack shape of the Björck family. We also note that this behavior improves with code length, in contrast to the quadratic phase codes.

In [4], we consider the use of frequency-coded sequences for adaptive waveform radar. We investigate the complementary ambiguity properties of stepped-frequency chirps, Costas sequences, and pushing sequences, and used these properties to develop an effective signal set for adaptive waveform radar for high-resolution delay-Doppler measurement. The proposed approach effectively sidesteps the difficult ambiguity-state estimation associated with the general statement of this problem.

In [5], we describe a method of constructing a sequence of phase coded waveforms with perfect autocorrelation in the presence of Doppler shift. The constituent waveforms are Golay complementary pairs which have perfect autocorrelation at zero Doppler but are sensitive to nonzero Doppler shifts. We extende this construction to multiple dimensions, in particular to radar polarimetry, where the two dimensions are realized by orthogonal polarizations. Here we determine a sequence of two-by-two Alamouti matrices where the entries involve Golay pairs and for which the sum of the matrix-valued ambiguity functions vanish at small Doppler shifts. The Prouhet-Thue-Morse sequence plays a key role in the construction of Doppler resilient sequences of Golay pairs.

Space-time codes built out of Alamouti components have been adopted in wireless standards such as UMTS, IEEE 802.11n and IEEE 802.16 where they facilitate higher data rates through multiplexing of parallel data streams and the addition of two or more antennas at the receiver that perform interference cancelation. In [6], we provide new theoretical insight into different algorithms for interference cancelation through a Bayesian analysis that expresses performance as a function of SNR in terms of the ”angles” between different space-time coded data streams. Our approach provides insights into the coupling of channel coding to spatial and polarization degrees of freedom.

1.2 Channel and Environment Modeling

Compound-Gaussian models are used in radar signal processing to describe heavy-tailed clutter distributions. The important problems in compound-Gaussian clutter modeling are choosing the texture distribution, and estimating its parameters. Many texture distributions have been studied, and their parameters are typically estimated using statistically suboptimal approaches. In [7], we develop maximum likelihood (ML) methods for jointly estimating the target and clutter parameters in compound- Gaussian clutter using radar array measurements. In particular, we estimate i) the complex target amplitudes, ii) a spatial and temporal covariance matrix of the speckle component, and iii) texture distribution parameters. Parameter-expanded expectationmaximization (PX-EM) algorithms are developed to compute the ML estimates of the unknown parameters. We also derived the CramrRao bounds (CRBs) and related bounds for these parameters. We first derive general CRB expressions under an arbitrary texture model then simplify them for specific texture distributions. We consider the widely used gamma texture model, and propose an inverse-gamma texture model, leading to a complex multivariate clutter distribution and closed-form expressions of the CRB.We study the performance of the proposed methods via numerical simulations.

The inverse gamma distributed texture is important for modeling compound-Gaussian clutter (e.g. for sea reflections), due to the simplicity of estimating its parameters. In [8], we develop maximum-likelihood (ML) and method of fractional moments (MoFM) estimates to find these distribution parameters.We compute the Cramer-Rao bounds (CRBs) on the estimate variances and present numerical examples. We also show examples demonstrating the applicability of our methods to real lake-clutter data. Our results illustrate that, as expected, ML estimates are asymptotically efficient, and also that the real lake-clutter data can be very well modeled by the inverse gamma distributed texture compound-Gaussian model.

A class of linear time-varying systems can be characterized by dispersive signal transformations such as nonlinear shifts in the phase of the propagating signal, causing different frequencies to be shifted in time by different amounts. In [9], we propose a discrete time-frequency model to decompose the dispersive system output into discrete dispersive frequency shifts and generalized time shifts, weighted by a smoothed and sampled version of the dispersive spreading function. The discretization formulation is obtained from the discrete narrowband system model through a unitary warping relation between the narrowband and dispersive spreading functions. This warping relation depends on the nonlinear phase transformations induced by the dispersive system. In order to demonstrate the effectiveness of the proposed discrete characterization, we investigate acoustic transmission over shallow water environments that suffers from severe degradations as a result of modal frequency dispersions and multipath fading. Using numerical results, we demonstrate that the discrete dispersive model can lead to a joint multipathdispersion diversity that we achieve by properly designing the transmitted waveform and the reception scheme to match the dispersive environment characteristics.

Stochastic models of sea clutter are mainly focused on the use of the K-compound distribution; nevertheless, these models generate random sequences of clutter that do not always rely on the physical conditions under which clutter itself is expected. Recently, new deterministic models of the sea based on fractal theory have been formulated that seem to get a better understanding of the physical behavior of this kind of surfaces. In [10], we intend to provide some improvements to previously published works on the subject by (1) using spherical waves instead of plane wave; (2) introducing multiple reflections and scattering factors; and, (3) representing the sea surface as an impedance surface. Physical optics will be used to solve the back-scattered field integral equations.

1.3 Performance Analysis

In [11], we consider the problem of passive estimation of source direction-of-arrival (DOA) and range using polarization sensitive sensor arrays, when the receiver array and the signal source are near the sea surface. The scenario of interest is the case of low-grazing-angle (LGA) propagation in maritime environments. We present a general polarimetric signal model that takes into account the interference of the direct field with the field reflected from smooth and rough surfaces. Using the Cramer-Rao bound (CRB) and mean-square angular error (MSAE) bound, we analyze the performance of different array configurations, which include an electromagnetic vector sensor (EMVS), a distributed electromagnetic component array (DEMCA), and a distributed electric dipole array (DEDA). By computing these bounds, we show significant advantages in using the proposed diversely polarized arrays compared with the conventional scalar-sensor arrays.

1.4 Adaptive Sensing and Probing Strategies

In [12], we cast the problem of optimal measurements as a problem of the optimal control of the Riccatti Equation associated with the error covariance of optimal estimates (given by the Kalman Filter) of the state of a linear system. We show that adaptive measurement strategies can be obtained by optimal steering of the Riccatti equation. Applications of these ideas to adaptive waveform design for radar are discussed in detail. We show that the ambiguity function of a Radar puts natural constraints on the set of available observations in the Riccatti equation. We present analytical solutions to these optimal control problems when the noise in the target dynamics is negligible.

1.5 Parameter Estimation

In [13], we develop optimal adaptive design of radar waveform polarizations for a target in compound-Gaussian clutter. We present maximum likelihood estimates of the targets scattering matrix and clutter parameters using a parameter-expanded expectation-maximization (PX-EM) algorithm. We compute the Cramer-Rao bound (CRB) on the targets scattering matrix. To design the polarization, we propose an algorithm that minimizes a CRB function. We propose also suboptimal versions of this algorithm and illustrate the performance as well as compare our algorithm with numerical examples.

In [14], we use an information theoretic approach to design radar waveforms suitable for simultaneously estimating and tracking parameters of multiple extended targets. Our approach generalizes the information theoretic water-filling approach of Bell to allow optimization for multiple targets simultaneously. Our paper has three main contributions. First, we present a new information theoretic design criterion for a single transmit waveform using a weighted linear sum of the mutual informations between target radar signatures and the corresponding received beams (given the transmitted waveforms). We provide a family of design criteria that weight the various targets according to priorities. Then we generalize the information theoretic design criterion for designing multiple waveforms under a joint power constraint when beamforming is used both at the transmitter and the receiver. Finally we provide a highly efficient algorithm for optimizing the transmitted waveforms in the cases of single waveform and multiple waveforms. We show that the optimization problem in both cases can be decoupled into a parallel set of low-dimensional search problems at each frequency, with dimension defined by the number of targets instead of the number of frequency bands used. The power constraint is forced through the optimization of a single Lagrange multiplier for the dual problem. We also provide simulated experiments of both algorithms based on real targets demonstrating the advantages of spectral shaping over spectrally flat waveforms. We end with comments on the generalization of the proposed technique for other design criteria, e.g., for the linearly weighted non-causal MMSE design criterion.

Instantaneous frequency (IF) estimation of signals with nonlinear phase is challenging, especially for online processing. In [15], [16], we propose IF estimation using sequential Baye-sian techniques, by combining the particle filtering method with the Markov chain Monte Carlo (MCMC) method. Using this approach, a nonlinear IF of unknown closed form is approximated as a linear combination of the IFs of non-overlapping waveforms with polynomial phase. Simultaneously applying parameter estimation and model selection, the new technique is extended to the IF estimation of multicomponent signals. Using simulations, the performance of this sequential MCMC approach is demonstrated and compared with an existing IF estimation technique using the Wigner distribution.

1.6 Target Detection

The dynamic adaptation of waveforms for transmission by active radar has been facilitated by the availability of waveform-agile sensors. In [17], we propose a method to employ waveform agility to improve the detection of low radarcross- section (RCS) targets on the ocean surface that present low signal-to-clutter ratios due to high sea states and low grazing angles. Using a subspace-based approach, we demonstrate that the correlation properties of compound-Gaussian sea clutter can be exploited to differentiate between the target and the clutter in a range bin, thus leading to improved detection performance. Estimates of the energy of the clutter at various ranges, obtained using the expectation-maximization algorithm, are used to design a phase-modulated waveform that minimizes the out-of-bin clutter contributions to the range bin of interest. This provides further improvement in detection performance.

In [18], we describe a new radar primitive that enables instantaneous radar polarimetry at essentially no increase in signal processing complexity. This primitive coordinates transmission of distinct waveforms on orthogonal polarizations and applies a unitary matched filter bank on receive. This avoids the information loss inherent in single channel matched filters. A further advantage of this scheme is the elimination of range sidelobes.

Sequential detection allows the analysis of an incoming data flow and detects the distribution change of these measurements. In [19], we develop a sequential detection algorithm for a target in compound-Gaussian clutter. Both the target and clutter parameters are assumed unknown. We first derive the estimates for these parameters, then discuss sequential detection algorithms for two cases: known and unknown target parameter. We consider detections for both the target appearance and disappearance. We examine the relationship between several performance measures for the sequential detector, including the false-alarm rate and the average detection delay. We finally illustrate the performance of our algorithms with numerical examples and present an example of the optimal polarimetry design in the sequential detection.

Polarization diversity has proved to be a useful tool for radar detection, especially when discrimination by Doppler effect is not possible. In [20], we address the problem of improving the performance of polarimetric detectors for targets in heavy inhomogeneous clutter. First, we develop a polarimetric detection test that is robust to inhomogeneous clutter. We run this polarimetric test against synthetic and real data to assess its performance in comparison with existing polarimetric detectors. Then, we propose a polarimetric waveform-design algorithm to further improve the target-detection performance. A numerical analysis is presented to demonstrate the potential performance improvement that can be achieved with this algorithm.

1.7 Target Tracking

The advent of waveform-agile sensors has enabled the design of tracking systems where the transmitted waveform is changed on-the-fly in response to the trackers requirements. This approach can provide performance improvements over individual optimization of the sensor waveform or the tracking algorithm. In [21], we consider joint sensor configuration and tracking for the problem of tracking a single target in the presence of clutter using range and range-rate measurements obtained by waveformagile, active sensors in a narrowband environment.We propose an algorithm to select and configure linear and nonlinear frequencymodulated waveforms to minimize the predicted mean square error (MSE) in the target state estimate; the MSE is predicted using the Cramer-Rao lower bound on the measurement error in conjunction with the unscented transform. We further extend our algorithm to match wideband environments, and we demonstrate the algorithm performance through a Monte Carlo simulation of a radar tracking example.

In [22], we develop an adaptive waveform design method for target tracking under a framework of sequential Bayesian inference. In our waveform design scheme we employ the freedom provided by the polarization of the transmitted signal to further improve the tracking accuracy. We use an array of electromagnetic (EM) vector sensors to receive the reflected signal. An EM vector sensor can fully exploit the polarization information by measuring the six components of the EM field. We apply a sequential Monte Carlo method to track the target parameters, including target position, velocity, and scattering coefficients. This method has the advantage of handling nonlinear and non-Gaussian state and measurement models. For optimal waveform selection we design a new criterion based on a recursion of a posterior Cramer-Rao bound. We also derive an algorithm using Monte Carlo integration to compute this criterion efficiently. Numerical examples demonstrate both the performance of the proposed tracking method and the advantage of the adaptive waveform design scheme.

In [23], we use a particle filtering method for tracking, in which each proposed particle location in the target state space is associated with a matched filter (MF) location in the delay-Doppler space. Resolution cells are formed using the exact shape of the thresholded ambiguity function and MF locations. This eliminates measurement errors associated with the traditional approach of using tesselating parallelogram resolution cells to approximate probability of detection contours, and omits the exhaustive search over all grid points. Assuming that the measurements resulting from each MF are independent reduces the computational complexity of our approach, and we show that independence primarily depends on the characteristics of the waveform used. We compare constant amplitude zero-autocorrelation coded (CAZAC) waveforms to linear frequency modulated ones, and demonstrate that Bjorck CAZACs provide smaller resolution cells and allow the use of the independence assumption without significant error.

1.8 Vector-Sensor Design

Polarization is one type of waveform diversity that may be exploited to improve both radar and communication systems performance. Prior analytical results show that in order to obtain the best performance improvements, based upon the use of polarization diversity, knowledge of the full electromagnetic field is required. Vector sensor antennas are able to measure more than one component of the electromagnetic field and thus enable the exploitation of polarization diversity. In [24]-[26], we describe co-located and distributed approaches to design a 6D vector antenna using both electric dipole and magnetic loops as constitutive elements.

1.9 Applications with NMR

In [27], we introduce algorithms based on Fourier synthesis for designing phase compensating radio-frequency (rf) pulse sequences for high-resolution nuclear magnetic resonance (NMR) spectroscopy in an inhomogeneous B0 field. We show that using radio frequency pulses and time varying linear gradients in three dimensions, it is possible to impart the transverse magnetization of spins a phase, which is a desired function of the spatial (x, y, z) location. Such a sequence can be used to precompensate the phase that will be acquired by spins at different spatial locations due to inhomogeneous magnetic fields. With this precompensation, the chemical shift information of the spins can be reliably extracted and high resolution NMR spectrum can be obtained. 3. Sensitivity enhanced recoupling experiments in solid state NMR by gamma preparation

In [28], we introduce a class of dipolar recoupling experiments under magic angle spinning (MAS), which use gamma dependent antiphase polarization during the t1 evolution period. We show that this helps us to design dipolar recoupling experiments that transfer both components of the transverse magnetization of spin S to a coupled spin I in the mixing step of a 2D NMR experiment. We show that it is possible to design such transfer schemes and make them insensitive to the orientation dependency of the couplings in powders. This helps us to develop sensitivity enhanced 2D NMR experiments of powder samples under MAS.

In [29], we show how non-selective radio frequency pulse sequences and time varying gradients can be used as probes to image and map spatially inhomogeneous B0 magnetic fields in magnetic resonance experiments. We provide algorithms for design of sequence of experiments consisting of radio frequency pulse sequences and time varying gradients that progressively minimize the line-width of the observed spectra. The design procedure ensures that reducing the line widths below a desired threshold amounts to learning the inhomogeneous field to a desired level of accuracy. The proposed algorithms for inferring the distribution of the inhomogeneous field are computationally efficient and can be implemented in real time applications. Once the inhomogeneous field distribution is known, we show that using radio frequency pulses and time varying linear gradients in three dimensions, it is possible to precompensate the phase that will be acquired by spins at different spatial locations due to inhomogeneous magnetic fields. With this precompensation, the chemical shift information of the spins can be extracted and high resolution NMR spectrum can be obtained.

The effciency of dipole-dipole coupling driven coherence transfer experiments in solid-state NMR spectroscopy of powder samples is limited by dispersion of the orientation of the internuclear vectors relative to the external magnetic field. In [30] we introduce general design principles and resulting pulse sequences that approach full polarization transfer efficiency for all crystallite orientations in a powder in magic-angle-spinning experiments. The methods compensate for the defocusing of coherence due to orientation dependent dipolar coupling interactions and inhomogeneous radio-frequency fields. The compensation scheme is very simple to implement as a scaffold (comb) of compensating pulses in which the pulse sequence to be improved may be inserted. The degree of compensation can be adjusted and should be balanced as a compromise between efficiency and length of the overall pulse sequence. We show by numerical and experimental data that the presented compensation protocol significantly improves the efficiency of known dipolar recoupling solid-state NMR experiment.

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1 Rationale

Conventional active sensing systems transmit fixed waveforms, i.e. with fixed parameters such as waveform shape, polarization, and frequency. Thus, the system operates in open loop, independently of the target and environment. However, in practice the target's states, including its position, velocity, and scattering coefficients, are unknown and could change during the sensing process; furthermore, the environment may also change, for example due to time-varying clutter or other interference. Hence, the fixed waveform might not match the operational scenarios and severely limit the sensing performance.

Recent advances in sensor information processing and related hardware have motivated intense interest in adaptive waveform design. Specifically, advances in flexible digital waveform modulators make it feasible to implement pulse-to-pulse, subarray-to-subarray waveform selection capability in real time. Thus, there is a strong interest in fully exploiting the potential of radar systems through adaptive waveform design to obtain the best performance.

In this project, we develop adaptive design of the transmitted waveform in response to unknown parameters of static and dynamic targets and time-varying environmental conditions. We demonstrate, though analysis, that the proposed methods provide dramatically improved performance over existing systems. Our project is multidisciplinary as we have experts in mathematics, statistics, engineering, and physics. The research of the team members span the areas of signal processing, radar, electromagnetics, information theory and communications.

2 Research

2.1 Waveform Design

2.1.1 Zero Autocorrelation Waveforms *(Benedetto)*

Problem Description
We analyzed a class of finite length, unimodular low correlation waveforms referred to as constant amplitude zero autocorrelation (CAZAC) waveforms. We constructed vector-valued CAZAC waveforms so as to model the multi-sensor and Golay-pair strategies of the other team members. For example, this leads to the theory of vector-valued ambiguity functions in MIMO systems.

Background
To the best of our knowledge, these are new research topics.

Progress
For future work, we will use finite frame Sigma-Delta quantization methods to implement diverse waveforms. These waveforms have desirable and constructible, but generally arbitrary phase. Effective low bit coding of this phase in noisy environments is necessary, and our new methods seem appropriate. We need to implement our theoretical results in practical situations to evaluate their scientific merit.

2.1.2 Ambiguity Function Analysis *(Benedetto)*

Problem Description
We performed ambiguity function analysis of multidimensional waveforms. The research on concatenation and averaging of Wiener and Bjorck waveforms continues as reflected by our publications.

Background
Our particular use of averaging and our introduction of Bjorck waveforms are new approaches.

Progress
These procedures lead to desirable ambiguity function localization properties. In addition, we performed theoretical analysis on the inversion of ambiguity function data, which are normally received

experimentally, leading to the construction of the underlying waveform. For future work, we must implement our theoretical results in practical situations to evaluate scientific merit.

2.1.3 Frequency and Phase Coded Waveforms *(Bell)*

Problem Description
We are currently investigating: (*i*) frequency-coded waveforms based on Costas and Pushing Sequences, and (*ii*) frequency and phase coded waveforms for multi-static radar. On the basic research side, we are looking at the construction and delay-Doppler resolution characteristics of these waveforms and developing decision strategies for adaptive waveform selection. On the technological side, we are developing a radar simulation program that computes the delay-Doppler response for arbitrary waveforms and pulse-trains.

Background
The progress of our predecessors in this area would primarily be the work of Costas, Golomb, and Levanon in the area of Costas sequences. There is little published work on these problems in the literature, however significant interest in further work in this area was expressed by AFOSR personnel at the Fall 2006 MURI review meeting.

Progress
We have completed most of the basic work on adaptive frequency coded waveforms and are currently looking at fine tuning the waveform selection strategies. We are currently developing the simulation tools to evaluate the waveform selection strategy for challenging target scenarios. In the area of frequency-coded multi-static waveform design, we are currently investigating the cross-ambiguity functions of Costas and pushing sequence waveforms in order to find good candidate waveforms. When good candidate waveforms are selected, they will be studied using initial work on bi-static ambiguity functions and simulation.

2.1.4 Doppler Resilient Waveforms *(Calderbank, Moran, Howard)*

Problem Description
We developed a method of constructing a sequence of phase coded waveforms with perfect autocorrelation in the presence of Doppler shift.

Background
The constituent waveforms are Golay complementary pairs which have perfect autocorrelation at zero Doppler but are sensitive to nonzero Doppler shifts.

Progress
We extended the former construction to multiple dimensions, in particular to radar polarimetry, where the two dimensions are realized by orthogonal polarizations. We determined a sequence of two-by-two Alamouti matrices where the entries involve Golay pairs and for which the sum of the matrix-valued ambiguity functions vanish at small Doppler shifts. The Prouhet-Thue-Morse sequence plays a key role in the construction of Doppler resilient sequences of Golay pairs.

2.1.5 Space-Polarization-Time Codes *(Calderbank, Howard)*

Problem Description
We provided a new theoretical insight into different algorithms for interference cancellation through a Bayesian analysis that expresses performance as a function of SNR in terms of the “angles” between different space-time coded data streams.

Background
Space-time codes built out of Alamouti components have been adopted in wireless standards such as UMTS, IEEE 802.11n and IEEE 802.16 where they facilitate higher data rates through multiplexing of parallel data streams and the addition of two or more antennas at the receiver that perform interference cancellation.

Progress
Our approach provides insights into the coupling of channel coding to spatial and polarization degrees of freedom.

2.1.6 Polarimetric Waveforms *(Nehorai)*

Problem Description
We applied diversely polarized signals to improve parameter estimation, detection and tracking performance of targets in adverse cluttered environments.

Background
Earlier work in the field of optimal polarization has addressed the selection of the optimum transmit antenna polarization under the assumption of known target scattering coefficients and disregarding the presence of any interference, such as noise or clutter.

Progress
We have developed adaptive polarimetric waveform methods for detecting and tracking targets in cluttered environments. Our results show that optimum selection of the transmit polarization yields improvement in the estimation of target and clutter parameters, target probability of detection, and tracking performance of a polarimetric radar.

2.1.7 Time-Frequency Waveforms *(Papandreou, Morrell)*

Problem Description
We developed a library of generalized frequency-modulated chirps with varying linear and nonlinear phase functions. These generalized chirps, such as linear, power and hyperbolic chirps, have an inherent immunity against multipath and Doppler, and are highly adaptable to dispersive media.

Background
Earlier work has investigated dynamic waveform selection for target tracking using linear models and with relatively limited waveform libraries. Interesting scenarios such as multiple targets, multiple sensors, and wideband environments have not been extensively investigated.

Progress
We have developed a dynamic waveform selection algorithm that tracks single or multiple targets with the minimum mean square tracking error as the optimization criterion. An unscented transform is used to linearize the observations model, while the Cramér-Rao bound is used to measure the relative performance of different generalized chirp waveforms. The algorithm has been applied successfully to a number of environments and scenarios including wideband, radar, sonar, single and multiple targets, perfect and imperfect detection, and the presence of clutter.

2.1.8 Information Theoretic Waveform Design *(Nehorai)*

Problem Description
We presented a new information theoretic design criterion for a single transmit waveform using a weighted linear sum of the mutual information between target radar signatures and the corresponding received beams. In addition, we generalized the information theoretic design criterion for designing multiple waveforms under a joint power constraint when beamforming is used both at the transmitter and the receiver.

Background
Previous research on waveform design was focused on single targets, even in the MIMO context. We are looking into design for extended targets (suitable for very wideband radars).

Progress
We are currently checking iterative techniques that iterate between the radar waveform and the beamformer design. Another issue is the choice of priority parameters that is required by the algorithm.

2.2 Environment/Channel Modeling

2.2.1 Dispersive Environment Characterization/Estimation *(Papandreou, Morrell)*

Problem description
A class of linear time-varying systems can be characterized by dispersive signal transformations such as nonlinear shifts in the phase of the propagating signal, causing different frequencies to be shifted in time by different amounts. We have developed algorithms for the online instantaneous frequency (IF) estimation of single or multiple component time-varying (TV) signals with highly nonlinear phase functions caused by these dispersive environments. The estimation can be achieved without prior knowledge of the signal or a closed form expression of the signal's phase function.

Background
Time-varying system representations based on spreading functions are important in many applications as they can provide a physical interpretation of the effects of the system on the input signal. However, spreading function representations are not practical as they are based on continuous formulations of the signal transformations with an uncountably infinite set of parameters. Discrete equivalent representations can be derived with a countably infinite or a finite number of sampled parameters. Once these representations are available, they could be useful for estimating signal parameters such as IF. Most parametric and non-parametric based IF estimation approaches, however, suffer either from a computational expense or the lack of exact mathematical models.

Progress
We have developed discrete time-frequency models to decompose the dispersive system output into discrete dispersive frequency shifts and generalized time shifts, weighted by a smoothed and sampled version of the dispersive spreading function. Using numerical results, we demonstrated that the discrete dispersive model can lead to a joint multipath dispersion diversity that we achieve by properly designing the transmitted waveform and the reception scheme to match the dispersive environment characteristics. A new approach for IF estimation using sequential Bayesian techniques has been developed, which combines the particle filter algorithm with the Markov Chain Monte Carlo (MCMC) method, and approximates the IF as a piecewise combination of IFs of non-overlapping waveforms with polynomial phase. We are currently developing a method to adapt the window length to recognize a rapid change of the IF.

2.2.2 Propagation Models *(Erricolo)*

Problem Description
We investigate propagation models for the electromagnetic field in maritime environments. We aim to improve current knowledge on the topic of deterministic propagation of electromagnetic waves over the sea. This research will enable the development of parametric models for their application in combination with optimization models of signal processing.

Background
Earlier research has considered fractal theory.

Progress
We are also considering the use of fractal theory because it allows for a good representation of the sea surface. In addition, we are currently investigating the use of spherical waves, rather than plane waves, for low-grazing angle applications and small targets.

2.2.3 Target Modeling *(Erricolo)*

Problem Description
We work on the computation of the diffracted field from elliptical objects using the incremental theory of diffraction (ITD). We aim to develop new diffraction coefficients that are based on the recently developed ITD method. These diffraction coefficients may then, in turn, be introduced in propagation models of the electromagnetic propagated field.

Background
To the best of our knowledge, there is no previous work discussing the ITD applied to elliptical objects.

Progress
We are currently working on the application of the theory.

2.2.4 Clutter Modeling *(Nehorai)*

Problem Description
We use compound-Gaussian models to describe heavy-tailed clutter distributions in radar signal processing. The problem consists of choosing the texture distribution of compound-Gaussian clutter model and estimating its parameters.

Background
Earlier work has considered non-Gaussian clutter modeling using log-normal, Weibull, and K distributions, as well as compound-Gaussian models with texture following a gamma distribution.

Progress
Using the inverse gamma distributed texture, we developed maximum likelihood (ML) methods for jointly estimating the target and clutter parameters in compound-Gaussian clutter.

2.3 Optimization

2.3.1 Adaptive Sensing and Probing Strategies *(Khaneja)*

Problem Description
We have focused on the problem of adaptive design of radar waveforms as a problem of optimally controlling the equation of error variance in estimating various target parameters like position, velocity, target type, etc. by appropriate choice of measurements. The choice of various parameters that characterize the waveform enter the dynamical equation of error variances as control parameters. The choice of the waveform should be such that it minimizes the error in tracking of a target. The problem of optimal adaptive measurements and waveform design reduce to optimal control of the Riccati equations with measurements entering as control variables.

Background
Optimal measurements and control of the conditional density equation has been extensively studied in the context of sensor networks and adaptive waveform design. There are numerous numerical strategies like particle filtering that have been developed. However, due to the increased complexity of the problem, it becomes impossible to obtain simple qualitative insight into this problem in this general setting. Our approach leads to adaptive waveform design solutions that can be qualitatively understood.

Progress
We have been studying the optimal control of the Riccati equations with the choice of the measurement matrix representing the control. We have analyzed the optimal control of the Riccati equations under various choices of performance measures. We have solved problems of optimal control of the Riccati equations, when the noise in the target dynamics is negligible. In our future work, we plan to investigate optimal control of the Riccati equations in the presence of noise in the target dynamics. Controlled Riccati equations form a rich paradigm to address problems of radar waveform diversity and design. Models are rich enough to consider continuous and discrete measurement, multiple targets, multiple radars and changing clutter and environment. Diverse modalities like spatial diversity, polarimetry, and power sharing can be addressed in this framework. This approach is novel and has a simplicity that leads to qualitative insights into the adaptive waveform design problem.

2.4 Target Detection

2.4.1 Adaptive Waveform Design for Detection *(Papandreou,Morrell,Moran,Howard,Calderbank)*

Problem Description
The detection of small targets on the ocean surface is a challenging problem due to low signal-to-clutter ratio (SCR) that results from low grazing angles and high sea state. Adaptive waveform design can be used to improve SCR and hence detection performance in areas of interest.

Background
A number of techniques for improving detection performance in clutter have been investigated. These generally assume the availability of prior estimates of clutter statistics and employ Gaussian models for clutter. Neither of these are usually available.

Progress
We have developed a dynamic waveform design algorithm that improves detection in heavy sea clutter by minimizing the effect of out-of-bin clutter in a range bin of interest. Using a two-stage procedure, we first estimate a putative target location and the clutter statistics in its neighborhood using the EM algorithm and a compound-Gaussian clutter model. This information is used to dynamically design a phase-modulated waveform that minimizes the smearing of out-of-bin clutter in the putative target location. Using numerical simulations based on real sea clutter data, performance gains of 10 dB SCR have been demonstrated.

2.4.2 Instantaneous Radar Polarimetry *(Calderbank, Moran, Howard)*

Problem Description
We developed a new radar primitive that enables instantaneous radar polarimetry at essentially no increase in signal processing complexity. This primitive coordinates transmission of distinct waveforms on orthogonal polarizations and applies a unitary matched filter bank on receive. This avoids the information loss inherent in single channel matched filters. A further advantage of this scheme is the elimination of range sidelobes.

Background
Conventional polarimetric systems transmit sequences of diversely polarized waveforms. Moreover, earlier research aimed to improve the matched filter response of the receiver in order to maximize resolution or minimize the effects of mismatching.

Progress
We are currently integrating these new physical layer functionalities with adaptive waveform selection (for example measurement that is a function of a particular range cell) and tracking. We expect to document at least 10 dB gains over the state of the art (adaptive CFAR developed by W. Dawber in the UK).

2.4.3 Polarimetric Detector for Targets in Heavy Inhomogeneous Clutter *(Nehorai)*

Problem Description
We addressed the problem of improving the performance of polarimetric detectors for targets in heavy inhomogeneous clutter.

Background
Previous relevant work describes optimal polarimetric detectors under the assumption of known target and clutter response, or depends on the application of training data.

Progress
First, we developed a new polarimetric detection test that is robust to inhomogeneous clutter, i.e. the detector false-alarm rate is insensitive to changes in the clutter, while still maintaining a good probability of detection. Our algorithm does not resort to secondary data. In addition, we propose a polarimetric waveform-design algorithm to further improve the target-detection performance. We use simulated and real data to show the advantages of our algorithms.

2.5 Target Tracking *(Benedetto, Calderbank, Howard, Moran, Morrell, Nehorai, Papandreou)*

Problem Description

We developed algorithms for waveform-agile sensing systems to improve the tracking performance of targets in challenging scenarios such as in the presence of heavy sea clutter.

Background

In earlier research, waveform design was used to reduce the effect of clutter and ensure track maintenance. However, not much progress was made where the waveform was adapted to the environment, and dynamic waveform selection was used with a class of waveforms with time-varying phase function characteristics.

Progress

Our research on waveform-agile sensing algorithms for tracking relies on different approaches. (*i*) The minimization of the predicted tracking mean square error (MSE) using the unscented transform. (*ii*) The minimization of the posterior Cramér-Rao bound (PCRB) using Monte Carlo integration. A particle filter is used to track the target and probabilistic data association was used in the presence of clutter. The best waveform for the next transmission is selected from a class of time-frequency signals and different polarizations; the waveform parameters are optimized through a grid search. We have obtained performance improvements of about 10 dB over a fixed linear chirp transmission.

As an alternative to the CRLB in high noise scenarios, we use a different approach based on resolution cells in the delay-Doppler plane. When the ambiguity function is only known numerically, the exhaustive computation of the likelihood function by the target tracker may become prohibitively expensive. Therefore, to be able to use this approach with waveforms such as CAZAC sequences, whose ambiguity function is not known in closed form but nevertheless possess excellent localization properties, we use particle filtering techniques to selectively interrogate those areas of the delay-Doppler plane where there is a high likelihood of the presence of the target. This permits the exact ambiguity contour to be used, thus minimizing measurement errors due to the approximation of the contours as parallelograms, and obviating the need for an exhaustive search over all grid points.

2.6 Waveform Diversity for Communications *(Zoltowski)*

Problem Description

We are working on the selection for a MIMO broadcast channel where independent data streams are transmitted to multiple users simultaneously using Dirty Paper Coding (DPC) schemes. For example, one basic results is that DPC actually achieves the capacity region of MIMO broadcast channels. The technological challenges center on the fact that the DPC scheme has a heavy computational load and can be sensitive to channel matrix rank. For the case where each user has only one antenna, a suboptimal scheme, termed as zero-forcing beamforming (ZFBF), can be employed to reduce the computational complexity. Other technological issues arise when the number of users is equal to the number of transmit antennas, for which the downlink channel matrix can sometimes be near-singular. One method investigated for mitigating this problem is to use a matrix perturbation method in conjunction with Tomlinson-Harashima precoding to achieve near-capacity performance.

Background

It has been shown that DPC can achieve the capacity region of MIMO broadcast channels. Jindal et al have developed an iterative water-filling approach to compute the DPC sum capacity of the MIMO broadcast channel based on the duality between the uplink multiple access channel (MAC) and downlink broadcast channel. In general, the search space of finding the optimal subset of M users is prohibitively large when the number of antennas K becomes large. To reduce the complexity, several suboptimal schemes have been proposed. For example, Goldsmith et al proposed the semi-orthogonal user selection (SUS) algorithm, and proved that, as K goes to infinity, this algorithm achieves a sum-rate that is very close to that of DPC.

Progress

Our work centers on developing a sequential water-filling (SWF) algorithm for user selection. The algorithm is based on the sequential nature of the user selection problem: when adding one user at a time, a one-step water-filling is sufficient; there is no need to go back and forth to find the users that ought to be allocated with nonzero power, as in classical water-filling strategies. In addition, the complexity of this algorithm is further reduced by an iterative procedure to calculate the Penrose-Moore inverse of a channel matrix based on LQ decomposition. The advantage of this algorithm, compared to prior work, is that it results in a subset of users that achieves a higher sum rate with significantly reduced complexity.

2.7 Vector-Sensor Design *(Erricolo)*

Problem Description
We work on the design, manufacture and test of vector-sensor antennas, using both co-located and distributed approaches. These sensors will allow to fully exploit the polarimetric information of the radar echoes, as well as to improve accuracy on the estimation of the target parameters. They will also have applications in communication systems with higher channel capacity.

Background
Most literature results contain theoretical discussions of what could be accomplishments if vector sensors were available.

Progress
We are working on different approaches: (*i*) a collocated approach, based on an extension of the work of Konanur et al., (*ii*) a collocated approach, based on an extension of the work of Kovalyov et al, and (*iii*) a distributed approach.

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Progress Report

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1 Rationale

In this project, we develop methods for adaptive design of signals transmitted by radar or communication systems. Such methods are aimed to optimize the performance in the presence of time-varying environmental conditions and, in the case of radar, respond to unknown parameters of static and dynamic targets. We devise algorithms that exploit the waveform diversities in multiple dimensions, such as time, space, frequency, phase, power, and polarization. We demonstrate, thorough analysis, that our proposed methods provide dramatically improved performance over existing systems.

In the last year we made significant progress in various aspects, including waveform design, channel modeling, algorithms for optimal waveform scheduling, methods for target detection and tracking, and waveform design for communication systems. Our contributions reflect the multidisciplinary subjects of the project and composition of our team. Namely, we have experts in mathematics, statistics, engineering, and physics. The research of the team members span the areas of signal processing, radar, electromagnetics, information theory and communications. In the following, we summarize in more detail our recent achievements.

2 Research

2.1 Waveform Diversity and Design

2.1.1 Ambiguity Function Analysis

Problem Description
After constructing new libraries of perfect autocorrelation (CAZAC) codes u and analyzing the ambiguity function behavior of phase coded waveforms defined in terms of u, it became essential to develop the vector-valued theory in order to analyze discrete time data vectors for d-element arrays. Further, the construction of CAZAC codes can be thought of in terms of constrained 1-bit Sigma-Delta quantization. As such, we are investigating the possible relations between CAZAC codes and constrained 1-bit Sigma-Delta quantization.

Background
To the best of our knowledge, our approach to formulating discrete periodic vector valued ambiguity functions in terms of the theory of frames is new. There is significant existing work on Sigma-Delta quantization. However, our effort to analyze quantitatively the relation of Sigma-Delta with fine quantization methods is original. Further, our constraints on low bit recursive quantization methods in terms of simultaneously generating quantization sequences with near perfect autocorrelation properties is new.

Progress
In [1]-[5], we have formulated meaningful definitions of $\mathbb{C}$ and $\mathbb{C}^d$ valued ambiguity function for vector- valued codes. This opens a large research area for more general formulation in terms of finite groups. There is also the technological problem of analyzing such ambiguity for vector-valued CAZACs which we have constructed last year. With success in these two thrusts, we shall have achieved great flexibility in waveform design. As regards, the constrained Sigma-Delta problem, we have completed the comparison with PCM and are now beginning the construction of recursive CAZAC codes.

2.1.2 Matched Segment Processing and Waveform Design for Enhanced Delay-Doppler Resolution

Problem Description
In [6]-[8], we considered the design of radar waveforms made of temporal segments that have low amplitude cross-ambiguity functions which can be used with a novel nonlinear processor to yield increased delay-Doppler resolution and sidelobe attenuation at the cost of a slight-to-modest reduction in detection performance. The novel nonlinear processor is based on models of neural processing

in echo-locating bats. A separate matched-filter Doppler filter bank is applied to each separate waveform segment, resulting in a separate delay-Doppler response map for each separate segment of the waveform. The delay-Doppler maps from each waveform segment are then combined using a family of nonlinear functions, resulting in a delay-Doppler response map with reduced ambiguity and enhanced resolution when compared to standard matched filter processing.

Background
To the best of our knowledge, this is entirely new work.

Progress
We showed analyzed the response of this processor for two-segment V-chirp and twin-Costas sequence waveforms processed using both a pointwise (in delay Doppler) product and minimum rule for combining segment delay-Doppler maps. In both cases, a significant decrease in ambiguity response occurs, with only slight artifacts in the multiple target case. We also investigated additional coded waveform designs to be used with this approach.

2.1.3 Doppler Resilient Waveforms

Problem Description
The development of phase coded waveforms that are Doppler resilient.

Background
The value of perfect autocorrelation sequences in radar imaging is that their impulse-like autocorrelation function can enable enhanced range resolution. Important examples of perfect autocorrelation sequences are complementary sequences introduced by Golay. These complementary sequences have the property that the sum of their autocorrelation functions vanishes at all (integer) delays other than zero. This means that the sum of the ambiguity functions (composite ambiguity function) of Golay complementary sequences is sidelobe free along the zero-Doppler axis, making them ideal for range imaging.

Despite their many intriguing properties and recent theoretical advances, in practice a major barrier exists in adoption of complementary sequences for radar and communications; the perfect autocorrelation property of these sequences is extremely sensitive to Doppler shift. Although the shape of the composite ambiguity function of complementary sequences is ideal along the zero-Doppler axis, off the zero-Doppler axis it has large sidelobes in delay, which prevent unambiguous range imaging in radar or reliable detection in communications.

Progress
In [9]-[11], we have documented a method of constructing a sequence of phase coded waveforms with perfect autocorrelation in the presence of Doppler shift. The constituent waveforms are Golay complementary pairs which have perfect autocorrelation at zero Doppler but are sensitive to nonzero Doppler shifts. We extend this construction to multiple dimensions, in particular to radar polarimetry, where the two dimensions are realized by orthogonal polarizations. Here we determine a sequence of two-by-two Alamouti matrices where the entries involve Golay pairs and for which the sum of the matrix-valued ambiguity functions vanish at small Doppler shifts. The Prouhet-Thue-Morse sequence plays a key role in the construction of Doppler resilient sequences of Golay pairs.

2.1.4 Time-Frequency Waveforms

Problem description
Waveform design is important for increasing detection, estimation, and tracking performance in agile sensing applications [12], [13]. We consider waveforms with arbitrary nonlinear time-frequency signatures, similar in form to waveforms used by bats or dolphins for echo-location, for use in waveform-agile tracking [14]-[16]. We developed a sequential Bayesian algorithm for estimating the instantaneous frequency of these waveforms in order to match bio-sonar waveforms for use in waveform agile sensing applications [17], [18].

Background

Earlier work has investigated dynamic waveform selection for target tracking using linear time-frequency variations. The use of waveforms with nonlinear time-frequency variations, such as generalized frequency-modulated (FM) chirps, has not been extensively investigated.

Progress
We developed a method to estimate an arbitrary time-frequency signature using a sequential Bayesian technique and piecewise combinations of non-overlapping windowed signals with polynomial phase. To more precisely match echo-location signatures, we have extended the method to multiple component signals by applying model selection with no a priori knowledge of the component number. We also adaptively choose the length of the non-overlapping windows in order to match rapid changes in time-frequency variation.

2.1.5 Adaptive Polarimetry Design for Targets in Compound-Gaussian Clutter

Problem Description
We applied diversely polarized signals to improve parameter estimation performance of targets in the presence of compound-Gaussian clutter.

Background
Earlier work in the field of optimal polarization has addressed the selection of the optimum transmit antenna polarization under the assumption of known target scattering coefficients and disregarding the presence of any interference, such as noise or clutter.

Progress
In [19], we developed an adaptive method for selecting the optimal polarization of the radar waveform for a target in compound-Gaussian clutter. We presented the maximum likelihood (ML) estimates of the targets scattering matrix and clutter parameters using a parameter-expanded expectation-maximization (PX-EM) algorithm. We computed the Cramér-Rao bound (CRB) on the targets scattering matrix and used it as the optimization cost function. We illustrated the performance of our algorithm and compared it with traditional ones through numerical examples.

2.1.6 Joint Transmitter and Receiver Polarization Optimization

Problem Description
We investigated the polarization optimization and power scheduling for the estimation of a target in a heavy clutter environment. We cast this problem as a nonlinear optimization problem for the optimal design of the radar polarization, which is further reformulated into a convex form and is thus numerically easily solvable.

Background
Radar systems have more robust performance by adapting their sensing patterns (or more specifically waveform polarization) to the operation scenarios (such as target, clutter etc.).

Progress
In [20], [21], we proposed a one-step optimization to select the optimal polarizations and power levels. We considered the optimal transmitter and receiver polarization for a polarimetric radar by adapting to the target and clutter polarimetric characteristics for enhanced sensing performance. The numerical results demonstrated that by carefully choosing the transmitter/receiver polarizations and pulse power levels, clutter interference can be efficiently suppressed. It is expected that additional performance gain can be achieved if such optimization is done sequentially on a pulse-by-pulse basis by using the most currently acquired information. In addition, we showed that to make the radar polarimetric sensing more efficient, multi-dimensional information of the incoming electromagnetic (EM) field at the radar receiver is simultaneously measured using, e.g., EM vector sensors.

2.1.7 Low Ambiguity Waveforms

Problem Description
The design of radar waveforms that have low ambiguity in both delay and doppler is a classical problem in Radar signal design. We have focused on improving the resolution of the waveforms by using an adaptive Radon transform. A train of pulses with different ambiguity profile illuminates the target and the matched filtered returns are then radon transformed adaptively along preferred directions. Combining adaptive probing and processing can lead to improved resolution. We have also studied the problem of adaptive design of radar waveforms as problem of optimally controlling the equation of error variance in estimating position and target, the Ricatti equations with measurements entering as control variables.

Background
There is a huge literature on design of coded waveform trains that have improved delay-Doppler resolution. These include Barker sequences, Costas Sequences, Frank codes, etc. There is also recent literature on using nonlinear processing for improving the resolution of the radar returns. Our work here describes how adaptive processing combined with adaptive probing can lead to enhanced delay-doppler resolution.

Progress
We can perform a radon transform of an image of the ambiguity function along certain direction and from the resulting radon transforms, we perform an inverse Radon transform (using the filtered back projection algorithm) to obtain a image that is well resolved in both the delay-doppler dimensions. In future work, we propose to study optimal sequence of these coded waveforms and use of other transforms for enhancing delay doppler resolution. We have also made progress on reverse engineering ambiguity functions to get waveforms that achieve the desired ambiguity profile. We have continued our work on study of controlled Riccatti equations and in general control of conditional density equations to address problems of Radar waveform diversity and design. In future, we plan to explore optimal probing of nonlinear control systems and optimal control of the conditional density equations that arise, especially in context of Bilinear control systems.

2.2 Environment and Channel Modeling

2.2.1 Clutter Covariance Estimation

Problem description
We developed a subspace based approach to exploit the correlation properties of compound-Gaussian sea clutter in order to differentiate between targets and clutter in a range bin. Estimates of the clutter energy, obtained using the expectation-maximization algorithm, are used to design a phase-modulated waveform that minimizes the out-of-bin clutter contributions to the range bin of interest [22]-[24] or maximizes the detection generalized likelihood ratio at the predicted target state [25]. We also developed a method to track the space-time covariance matrix of sea clutter in rapidly-varying radar scenes for use in adaptive target detection and tracking. The method uses multiple particle filtering to estimate the clutter scene scattering function [26]-[28].

Background
In radar applications, detection of a moving target in heavy sea clutter is a well-known and challenging problem. Low signal-to-clutter ratios (SCRs) make satisfactory performance difficult to achieve even for targets of large radar cross-section. Accurate estimation of the space-time covariance matrix of sea clutter at low SCRs is thus needed to enable improved detection performance. Although approaches to this estimation problem under slowly varying conditions have been proposed, situations in which the radar scene varies quickly present significant additional difficulties.

Progress
We dynamically estimate the space-time covariance matrix of low-SCR sea clutter by formulating the space-time representation of the clutter scene into the scattering function domain. We model the time evolution of the scattering function with a high dimensional dynamic system; a multiple particle filter technique is used to sequentially estimate the dynamic scene. The effectiveness of

this method is demonstrated by detecting a simulated moving target in heavy sea clutter. We are currently comparing our technique with a baseline approach that estimates the clutter covariance matrix based on the Weibull distribution approximation.

2.2.2 Shallow Water Environment Modeling

Problem description
We developed a general characterization based on the acoustic normal-mode model for shallow water environments [29]-[31]. The corresponding dispersive transformations on the transmit waveform match the proposed system model that can be exploited to achieve waveform diversity [32].

Background
For underwater communications, incoherent techniques were shown to lack the ability to adapt waveform parameters to changes in the environment, and they were highly inefficient with regard to bandwidth and power requirements. We have previously used high bandwidth transmitted waveforms to match the dispersive transformation caused by the shallow water environment. Our current scheme is suitable for both narrowband and wideband signals.

Progress
We developed a frequency-domain model of the shallow water medium that characterizes dispersive characteristics on transmitted waveforms. We used a blind time-frequency processing technique to separate the normal modes without a priori knowledge of the model parameters by first approximating the time-frequency structure of the received signal and then designing separation filters based on warping techniques. Currently, two types of receivers have been developed for agile sensing in communications so as to exploit diversity and improve underwater communication performance [33], [34].

2.2.3 LTV Systems and Compressive Sensing

Problem description
We developed compressive sensing based algorithms for estimating the spreading function characterization of linear time-varying (LTV) systems. We first design the transmitted waveform to match the environment, and then we use compressive sensing, based on the sparsity of the system characteristics, in order to reduce the number of measurements needed for the estimation [35], [36].

Background
Discretization of LTV system representations has enabled their use in obtaining different types of diversities, designing detection and estimation algorithms, and developing waveform-agile sensing algorithms. It is thus important to be able to estimate the parameters of LTV system representations for use to enhance system performance without requiring a large number of measurements.

Progress
The developed compressive sensing-based algorithms can be used to estimate environment spreading function representations for general LTV systems, including narrowband, wideband, and dispersive, with reduced data sets. We have currently extended the algorithm for use with real sensor measurements to be robust in the presence of noise.

2.2.4 CRB Using MIMO Radar

Problem description
We derived the Cramér-Rao bound (CRB) for estimating multiple target attributes for multiple-input, multiple-output (MIMO) radars [37], [38]. When the antennas are co-located, we estimate direction of arrival, range and range rate of the target. For widely-separated antennas, we estimate position and velocity of the target.

Background
Although recent studies have computed the CRB for estimating target attributes using MIMO radar,

target motion parameters (such as range rate or velocity) have not been considered. Knowledge of the CRB is important for waveform-agile sensing under high signal-to-noise ratio (SNR) assumptions.

Progress
The CRB on the target parameter covariance using MIMO radars with collocated antennas is developed and shown to generalize the CRB results using sensor arrays. The collocated antenna MIMO radar is a system that can transmit a different waveform in each antenna, and can thus exploit waveform diversity. The relationship between the CRB covariance matrix and the transmission waveform characteristics are currently being investigated as this is essential for use in waveform-agile sensing.

2.2.5 Exploiting Close-to-the-Sensor Multipath Reflections

Problem Description
In [39], we demonstrated that by exploiting close-range multipath reflections, originated from parts of the platform on which the sensor is mounted, we can improve the target-direction estimation.

Background
The conventional systems try to suppress or filter out the close-to-the-sensor multipath reflections by treating them as interference.

Progress
First, we proposed a simple three-dimensional (3D) direction-finding system that exploits multipath reflections close to the sensors and analyzed the performance of this system by computing the asymptotic frequency domain Cramér-Rao bound (CRB) on the error of the 3D direction estimate. Then, to demonstrate the effect of multipath reflections in more realistic scenario, we considered a simplified structure of an UAV and modeled the multipath propagations from body and wings using geometric optics (GO) and uniform theory of diffraction (UTD). In addition, we numerically computed the CRB on directional angles and found that the best positions for placing the sensors is below the wings, exploiting multipath reflections.

2.2.6 Fringe Formulation to Improve Physical Optics

Problem Description
In [40], [41], we investigateed physical optics based propagation models that take into account the interaction between general radiators and general scatterer configurations. We aimed at improving electromagnetic field prediction software by taking into account scattering effects that are not analyzed using simple physical optics methods. Such methods are fast, easy to implement, and they only require a contour integration of incremental coefficients along the rim of the scatterer, thus avoiding any expensive ray-tracing algorithm. This can be useful to predict the electromagnetic signature of objects when illuminated by any kind of antenna.

Background
Physical optics based methods may provide inaccurate predictions when considering illumination along directions away from principal lobes of radiation.

Progress
We are perfecting the scattering coefficients to correct physical optics and extending them to the case of complex point sources using Gabor series representation of a radiated field.

2.2.7 Multistatic Radar: relation between the Green Function and the Ambiguity Function

Problem Description
In [42], we investigated the relationship between the Green's function and the corresponding ambiguity function for the MIMO radar problem. Multistatic radars hold the potential of substantially

improving the accuracy of detection, estimation, and tracking of targets compared to monostatic radars. The improvements come from the fact that the target is illuminated from several different directions, and it is observed from other directions (geometrical diversity). Finding a way to relate the Green's function for the environment where a multistatic radar system operates and the multistatic ambiguity function would provide great help in the design of appropriate waveforms to improve multistatic radar performance.

Background
In monostatic radars, the target return is expressed parametrically in terms of target's position and radial velocity. A simple receiver consisting of a matched filter and a threshold detector is commonly employed to estimate the target parameters, and the detector performance is then presented in terms of the ambiguity function, which relates the estimation error to the system Green's function. The same framework has been extended to single transmit and single receive bistatic radar.

Progress
Work is in progress to derive the relationship between the Green's function and the corresponding ambiguity function for the MIMO radar problem, which is determined by the system geometry and the propagation characteristics of the transmitted pulse. This, in turn, impacts the error variance of signal processing algorithms for target parameter estimation in a MIMO radar setting.

2.2.8 RF Tomography

Problem Description
In [43]-[47], we investigated a new technique for buried object detection and location based on radio frequency tomography. With this method, information concerning the targets is greatly improved thanks to view diversity, observation diversity, polarization diversity, and antenna pattern diversity. In this way, the frequency content of the probing signal can be drastically reduced up to the monochromatic situation, while the object resolution can be still in the sub-wavelength region. We considered the propagation to occur in a half space environment: this approach allows us to extend this theory to other critical problems, such as the detection of metallic objects in proximity of the sea surface.

Background
Earlier research has considered seismic and electromagnetic sensing of the underground. Novel approaches include the perforation of boreholes and the use of tomographic inversion schemes. However, these methods are intended for exploration surveys, where drilling boreholes and logging equipment may be highly time-consuming and expensive. Furthermore, buried object detection has been applied for very shallow or very deep investigation, leaving the range of depth 5-200 meters practically unexplored. In addition, conventional methods require the operator to be in situ: this condition may be risky when the environment is harsh or inaccessible.

Progress
Increasing the information by using multiple diversities, the complexity of the system has been moved from the physical sensor technology to the signal and image processing. We defined a forward propagation model (for the half space case) that can be expressed as linear integral form. In deriving this model, we expressed the Sommerfeld integrals in a closed form, so that we were able to construct a dyadic Green's function for the half-space case that is not in a spectral form. Using this model, we derived several tomographic inversion schemes that are fairly robust to noise and clutter. Currently, we are investigating the actual performance of this method in noisy and cluttered environments, the maximum and minimum range of operation, and the maximum resolution achievable as a function of the sensors deployed in the ground.

2.3 Optimization

2.3.1 Optimal Polarized Beampattern Synthesis

Problem Description
We considered the beampattern synthesis with polarization constraints using an array of vector antennas consisting of electric and magnetic dipole elements. We formulated the problem in a convex form, for which the design variables are the amplitudes and phases of the weights in the antenna elements, and the polarization condition is cast in a linear constraint.

Background
In radar, polarimetric information in the backscattered waveforms contains the targets features such as geometrical structure, shape, reflectivity, orientation, etc., and can thus be exploited to significantly improve the sensing performance. To acquire complete polarimetric information of the target, it is desirable for radar to be able to control the transmit waveform polarization which in addition enables the transmit polarization diversity.

Progress
In [48]-[50] we showed that for arrays consisting of 2D vector antennas, when each antenna is compromised of a pair of co-aligned electric and magnetic dipoles, it has the same capability of suppressing the sidelobe power density as the corresponding scalar arrays of electric or magnetic dipoles. However, the vector array has the additional capability of controlling the beam polarization. For array of vector antennas with number of dipole elements $p \geq 2$ in each antenna, we showed that the power gain achieved by the array is linearly proportional to p. This reveals that for a vector antenna array, it does not only enables polarization control, but also virtually increases the array size by exploting multiple EM fields at each physical point.

2.4 Target Detection

2.4.1 Waveform-Agile Detection in High Sea Clutter

Problem description
We developed a waveform design algorithm for detecting targets in rapidly-varying radar scenes [51]. The algorithm first estimates the sea clutter statistics under low SCR, and then it uses the statistics to adaptively design the transmitted waveform for the next time step.

Background
Many methods have been proposed on target detection but most work well only under slowly-varying conditions. Optimization of the transmitted waveform to increase detection performance is thus very beneficial for rapidly-varying clutter scenes.

Progress
The waveform-agile detection algorithm in low SCR first tracks the clutter scattering function at each burst by estimating the clutter's space-time covariance matrix. The parameters of a phase-modulated waveform are then selected at the next time burst by maximizing the generalized likelihood ratio at the predicted target state, thus improving the SCR. We are currently exploring the use of the estimated clutter statistics in waveform-agile tracking.

2.4.2 Adaptive Design of OFDM for Target Detection

Problem Description
In [52], we proposed an algorithm to improve target-detection performance by adaptively designing the transmitting-spectrum of an OFDM radar.

Background
In earlier research, the OFDM signalling was used with fixed transmitting spectrum that was not adapted to the target response.

Progress
We presented an algorithm for detecting a moving target using an orthogonal frequency division multiplexing (OFDM) radar. First, we developed a parametric model that accounts for the measurements at multiple frequencies as well as Doppler shift. Then, we introduced a statistical detection test and evaluated its performance characteristics. Based on the asymptotic performance analysis, we proposed an algorithm to adaptively design the spectrum for the next transmitting waveform in order to maximize the probability of detection.

2.4.3 Reconstruction of a Sparse Scattering Field by Compressive Sensing

Problem Description
The objective is reconstruction of a sparse scattering field from radar returns by means of compressive sensing.

Background
The essential idea in work of Herman and Strohmer is that the return from a radar scene will generally be a sparse superposition of time-shifted and (under narrowband approximation assumptions) frequency-shifted replicates of the transmitted waveform. The compressive sensing concept thus suggests that a few projections onto measurement functions incoherent with this sparsity set should be sufficient to identify which elements of the sparsity set are present in the return, thereby providing a high-resolution analysis of the scene.

Progress
We have been looking at coding-theoretic constructions of sensing matrices for radar and other applications. Princeton graduate student Lorne Applebaum has developed chirp-based based sensing matrices. The columns of these matrices are discrete chirp waveforms from an overcomplete dictionary. We have developed algorithms for recovering a sparse vector from an overcomplete chirp dictionary (see MURI 2007 Report).

The wideband receiver developed by Rob Nowak (Wisconsin) to capture sparse superpositions of pure tones as part of the A-to-I project (DARPA, Dennis Healy) leads to a very similar problem. If the A/D samples at the level crossings of a chirp waveform, then the A/D output samples are discrete chirp sequences, and so the sparse narrowband recovery problem amounts to determining a small number of chirps that agree with the sampled data.

This reduces to essentially the same problem under investigation in our MURI project. The synergy between the two projects has led to some important new insights. First, using ideas from compressed sensing developed in A-to-I program, we have established new theoretical bounds for stable and robust signal recovery using the chirp-based sensing matrices. We also believe that these results will help to rigorously quantify the performance capabilities of the L3 architecture for A/D conversion. The fast solvers for signal recovery using chirp-based sensing matrices are expected to lead to fast algorithms for the L3 architecture.

2.5 Target Tracking

2.5.1 Bat-Inspired Adaptive Design of Waveform and Trajectory for Target Tracking

Problem Description
We considered the problem of joint design of the waveform and trajectory of a radar mounted on a moving platform. We developed an adaptive algorithm, inspired on the behavior of bats, to improve the tracking performance of maneuvering targets.

Background
Bats are capable of detecting and catching a fast moving prey, even in dense cluttered environments. Studies of the echo-location system of these mammals show that bats change the parameters of the transmitted sound during different stages of the target pursuit sequence. For instance, they increase

the pulse repetition frequency (PRF) to refine range information when they are close to the prey. In addition, they adapt their flight path based on the predicted target trajectory.

Progress
In [53], we developed an adaptive algorithm that, at each time step, optimally selects the radar actions in response to the estimated and predicted target parameters to improve the tracking accuracy. We derived our approach under a framework of sequential Bayesian filtering and used particle filters to handle the case of nonlinear measurement models. We designed the criterion for the optimization based on the posterior Cramér-Rao bound. In [54] we first applied this framework to design the trajectory of a moving radar. Then, in [55] we included the design of the waveform parameters jointly with the radar path.

2.5.2 Multiple Target Tracking Using CAZACs

Problem description
When tracking multiple targets with radar [56], [57], measurements from weak targets are often masked by the ambiguity function (AF) sidelobes of measurements from strong targets. As this can deteriorate the joint tracking performance, we developed a transmission scheme to improve multiple tracking performance. The scheme consists of multi-carrier phase coded (MCPC) Bjorck CAZAC waveforms whose AF sidelobes can be adaptively positioned in such way as to unmask weak targets [58]-[61].

Background
Adaptive waveform selection in the literature deals mostly with linear models and single targets. The problem of multiple target tracking in a nonlinear settings, and especially tracking of weak targets in the presence of strong targets, has not been dealt with extensively.

Progress
We combine different cyclically-shifted CAZACs whose AF surfaces have sidelobes whose locations depend on the difference in cyclic shift, number of sequences, and sequence length. The CAZACs are combined using an MCPC scheme, and the MCPC waveforms are transmitted using orthogonal frequency division multiplexing (OFDM). We developed an algorithm to adaptively position the AF sidelobes by selecting the parameters of the transmitted MCPC CAZAC waveform to minimize the predicted mean-squared tracking error. We also implement a likelihood particle filter and an independent partitions proposal method to track multiple targets using the extremely high resolution measurements provided by the CAZAC waveforms.

2.5.3 Frequency-Agile Tracking in Shallow Water

Problem description
Following the matched field processing framework, we developed an algorithm to adaptively select the observation frequencies of multiple sensors in a shallow water environment in order to improve target localization and tracking performance [62], [63]. We also developed implementation-aware algorithms to reduce the computational complexity of sequential Monte-Carlo techniques used for tracking [64], [65].

Background
In underwater source localization and tracking applications, a sensor array is normally used to find the best match between measured and modeled array outputs. We use a sensor parameter selection framework that is formulated in terms of a widely-used model for maneuvering targets and the sound field shallow water environment representation.

Progress
We consider multiple passive acoustic sensors that are distributed at different positions in the water column to collect data to correctly locate and track a target in a shallow water environment. We developed a dynamic frequency-agile sensing algorithm to minimize the predicted mean-squared error of the state estimates in order to enhance the tracking algorithm performance. Each sensor can select its own observation frequency and position parameters to optimally estimate the target's

location and velocity. However, as the dimension of the adjustable sensor parameters increases, the grid search optimization method is no longer feasible for the parameter scheduling, and a sequential quadratic programming algorithm is used instead.

2.5.4 Waveform-Aagile Tracking for Low SNR

Problem description
We designed a dynamic waveform selection algorithm for tracking radar targets in low SNR environments using AF resolution cells to find the measurement noise covariance matrix [66].

Background
Waveform-agile tracking algorithms usually make the assumption of high SNR in order to use the CRB waveform-dependent formulation in minimizing the predicted mean-squared error (MSE). This formulation considers only the mainlobe of the AF and ignores the sidelobes due to the assumed low noise levels. However, most realistic scenarios cannot make that assumption.

Progress
We propose a method for waveform-agile tracking under high noise conditions that uses AF waveform-dependent resolution cells in the selection algorithm. As the resolution cell can be adapted to include any number of AF sidelobes, the waveform selection algorithm can also be used in low SNR tracking scenarios.

2.5.5 Waveform-Agile Estimation in MIMO Radar

Problem description
We investigated a waveform-agile algorithm to select waveform parameters to improve the maximum-likelihood estimation (MLE) performance of the range and direction-of-arrival (DOA) of a target using a MIMO radar system with colocated antennas. The CRB was used as the performance bound for the joint estimation [67].

Background
Earlier work used the CRB in MIMO radar applications to design a random transmission waveform according to the desired beam pattern. However, the CRB for the joint range-DOA estimation was not used before to select transmit waveform parameters.

Progress
We investigated the CRB for the joint estimation of range and DOA using MIMO radar with colocated antennas, and we compared it to the estimation performance of the MLE. Under high SNR conditions, minimizing the estimation MSE corresponds to minimizing the CRB, and the CRB can be expressed in terms of the parameters of the transmitted waveform. Using linear FM chirps, we demonstrated that the covariance of the MLE is in close agreement with the CRB, thus validating the use of the CRB as the optimization performance criterion. We are currently investigating the use of other generalized FM chirps as possible choices of transmitted waveforms.

2.5.6 MIMO Radar with Diversity

Problem description
We investigated a waveform design technique using MIMO radar with widely-separated antennas for dynamic target tracking [68]. We also developed a new approach that uses a MIMO radar with collocated antennas that can greatly reduce target fluctuations by the use of frequency diversity [69]. This technique can significantly improve radar detection and estimation performance under varying environmental conditions.

Background
Currently, MIMO radars with colocated and widely-separated antennas have been studied in the literature. Although space-diversity can be achieved with widely-separated antennas, such systems face time and phase synchronization issues. Systems with colocated antennas can provide waveform-

diversity, however they cannot reduce target fluctuations as they cannot offer space diversity. The new system offers the alternative of frequency diversity to reduce target fluctuations.

Progress
For waveform-agile tracking using widely-separated MIMO radar, we used the CRB on target location and velocity estimation, which is represented by the waveform parameters. Based on the parameterized CRB, we minimize the predicted MSE for target tracking by adaptively selecting the optimum parameters of the transmission waveform. For frequency-diversity, we proposed a transmitter and receiver architecture for MIMO radar with colocated antennas. The radar cross-section of a complex target varies with transmitted frequency; as long as the frequencies are widely-separated so that the reflection coefficients corresponding to different frequencies are uncorrelated, by transmitting multiple frequencies at the same time we can achieve diversity by appropriately combining the resulting responses. The system results in a radar array with frequency-division multiplexing that can also incorporate beamforming to design the transmission beam pattern.

2.6 Waveform Diversity for Communications

2.6.1 Code Diversity in Multiple Antenna Wireless Communication

Problem Description
The problem is to quantify the value of adaptivity in multiple antenna wireless communication and to develop very low complexity methods that are able to realize that value.

Background
The standard approach to the design of individual space-time codes is based on optimizing diversity and coding gains. This geometric approach leads to remarkable examples, such as perfect space-time block codes, for which the complexity of Maximum Likelihood (ML) decoding is considerable.

Progress
In [70]-[72], we have developed an approach which we call Code Diversity where a small number of feedback bits are used to select from a family of space-time codes. Different codes lead to different induced channels at the receiver, where Channel State Information (CSI) is used to instruct the transmitter how to choose the code. This method of feedback provides gains associated with beamforming while minimizing the number of feedback bits. Thus code diversity can be viewed as the integration of space-time coding with a fixed set of beams. It complements the standard approach to code design by taking advantage of different (possibly equivalent) realizations of a particular code design. Feedback can be combined with sub-optimal low complexity decoding of the component codes to match ML decoding performance of any individual code in the family. It can also be combined with ML decoding of the component codes to improve performance beyond ML decoding performance of any individual code. One method of implementing code diversity is the use of feedback to adapt the phase of a transmitted signal.

2.6.2 SINR-Max Cooperative Beamforming in Multiuser MIMO Systems

Problem Description
For uplink multiuser communications, it is possible for each user to obtain the full multiuser channel state information. We addressed the problem of maximizing the signal-to-interference-noise ratio of each user by exploiting the advantage of the full multiuser channel state information available at the transmitters.

Background
In our previous work, we proposed an SINR-Max cooperative beamforming algorithm to maximize the signal to multiuser interference plus noise ratio (SINR) for individual users at the output of the multiuser detector.

Progress
We extended the application of SINR-Max cooperative beamforming to frequency selective block invariant channels [73] by combining orthogonal frequency division multiplexing technique into MIMO

systems . Furthermore, we proposed two iterative algorithms [74] to solve for the exact SINR-Max cooperative beamforming.

2.6.3 Multiple Antenna Broadcast Channels With Shape Feedback and Limited Feedback

Problem Description
Because of the need for high data rate multiuser systems, it is imperative to understand how to leverage multiple antenna technology to increase the data rate and user capacity of wireless networks. We addressed the problem of designing a point-to-point multiple antenna signal using some form of partial channel state information at the base station transmitter (CSIT).

Background
For multiple antenna broadcast channels, the partial CSIT problem is not as well addressed as in the single-user MIMO case.

Progress
We considered two different CSIT models [75]: the shape feedback model and the limited feedback model. Intuitively speaking, a system with shape feedback loses the sum rate gain of adaptive power allocation. However, shape feedback still provides enough channel knowledge for zero-forcing dirty paper coding (ZFDPC) and channel inversion (CI) to approach their own optimal throughput in the high signal-to-noise ratio (SNR) regime. For limited feedback, we derived sum rate bounds for both ZFDPC and CI and linked their throughput performance to some basic properties of the quantization codebook. We found that limited feedback employing a fixed codebook leads to a sum rate ceiling for both schemes for asymptotically high SNR.

2.7 Vector-Sensor Design

2.7.1 A MIMO Cube Antenna

Problem Description
In [76], we designed, manufactured, and tested a prototypes of vector-sensor antennas, using both co-located and distributed approaches. These sensors will allow to fully exploit the polarimetric information of the radar echoes, as well to improve accuracy on the estimation of the target parameters. They will also have applications in communication systems with higher channel capacity.

Background
Most literature results contain theoretical discussions of what could be accomplishments if vector sensor were available.

Progress
We developed simulations and now are about to start manufacturing a vector sensor that is based on loop and dipole antennas built on the 6 faces of a cube.

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Contents

1 Rationale **2**

2 Research **2**

2.1 Waveform Diversity and Design . . . 2

2.1.1 Ambiguity Function Analysis . . . 2

2.1.2 Adaptive Design of OFDM based on Ambiguity Function . . . 2

2.1.3 OFDM MIMO Design for Low-Angle Tracking Using Mutual Information . . 3

2.1.4 Radar Waveforms with Ambiguity Functions Free of Sidelobes inside a Desired Range or Doppler Interval . . . 3

2.1.5 Matched Segment Processing and Waveform Design for Enhanced Delay-Doppler Resolution . . . 4

2.1.6 Sampling Techniques for Low Ambiguity Waveforms by Adaptive Radon Transforms . . . 5

2.1.7 Unitary Waveform Design for MIMO Systems . . . 5

2.2 Environment and Channel Modeling . . . 7

2.2.1 Fringe Formulation (ITD+ Physical Optics Endpoints) to Augment Physical Optics . . . 7

2.2.2 Enhancing Radar Ambiguity . . . 7

2.3 Target Detection . . . 8

2.3.1 MIMO Radar Detection and Adaptive Design in Compound-Gaussian Clutter 8

2.3.2 Polarimetric MIMO Radar with Distributed Antennas for Target Detection . 8

2.3.3 Target Detection with Waveform Design in Rapidly-varying Radar Scenes . . 9

2.3.4 Urban Waveform-agile Detection and Multipath Exploitation . . . 9

2.4 Target Tracking . . . 9

2.4.1 Waveform-agile Target Tracking Using MIMO Radar . . . 9

2.4.2 Waveform-agile Estimation Using MIMO Radar . . . 10

2.4.3 Sensor Scheduling with Waveform-agility for MIMO Radar Target Tracking . 10

2.4.4 Urban Waveform-agile Tracking and Multipath Exploitation . . . 11

2.5 Waveform Adaptivity in Communications . . . 11

2.5.1 Waveform Adaptivity in Multi-antenna Wireless Communications . . . 11

2.6 Compressive Sensing for DOA Estimation and Radar . . . 12

2.6.1 Performance Analysis for Sparse Support Recovery . . . 12

2.6.2 Feasibility of the Reconstruction of a Sparse Scattering Field . . . 12

2.7 Through the Wall Radar . . . 13

2.7.1 An approach to estimating building layouts using radar and jump-diffusion algorithm . . . 13

2.7.2 Estimating moving targets behind reinforced walls using radar . . . 14

2.7.3 Exploiting multipath from airborne platforms for improved direction of arrival estimation . . . 14

2.7.4 RF Tomography: Underground Void Detection . . . 14

2.8 Other Published Work . . . 15

1 Rationale

In this project, we develop methods for adaptive design of signals transmitted by radar or communication systems. Such methods are aimed to optimize the performance in the presence of time-varying environmental conditions and, in the case of radar, respond to unknown parameters of static and dynamic targets. We devise algorithms that exploit the waveform diversities in multiple dimensions, such as time, space, frequency, phase, power, and polarization. We demonstrate, thorough analysis, that our proposed methods provide dramatically improved performance over existing systems.

In the last year we made significant progress in various aspects, including waveform design, environment modeling, algorithms for target detection and tracking, waveform adaptivity in communications, compressive sensing and through-the-wall radar. Our contributions reflect the multidisciplinary subjects of the project and composition of our team. Namely, we have experts in mathematics, statistics, engineering, and physics. The research of the team members span the areas of signal processing, radar, electromagnetics, information theory and communications. In the following, we summarize in more detail our recent achievements.

2 Research

2.1 Waveform Diversity and Design

2.1.1 Ambiguity Function Analysis

Problem Description
We continue to construct perfect autocorrelation (CAZAC) sequences, and are now systematically upgrading our CAZAC MATLAB-based computational software to implement these sequences, and to analyze the narrow-band and wide-band ambiguity functions of CAZAC phase-coded waveforms. Also, because of MIMO and multi-sensor array considerations, we have continued to develop our vector-valued ambiguity function theory first exposited at Asilomar 2008. The next step, which is driving our present research, deals with the formulation of vector-valued discrete Fourier transform (DFT) theory with corresponding uncertainty principle inequalities associated in compressive sampling theory with sparse representations.

Background
To the best of our knowledge, our vector valued approach to ambiguity functions, DFTs, and uncertainty principle inequalities in terms of frames is new. Further, by tying-together the uncertainty principle inequalities with sparse representations we are providing a nexus between our vector-valued theory and our low-bit optimization-based recursive quantization methods, see [1]. There is a relationship between these latter methods and the construction of CAZACs, which we are pursuing.

Progress
Much of the vector-valued DFT theory and uncertainty principle inequalities has been developed, and it is in [2]. The wide-band ambiguity function and Björck CAZAC simulations are part of the CAZAC software [3], cf., [4] for background to Björck sequences. The construction of infinite CAZAC sequences is the subject of [5] and it uses Hadamard sequences in a new way. This led to the relationship between CAZACs and multiresolution analysis, see [6]. The results of [7], on new geometrical properties of Shapiro-Rudin polynomials, are meant as a step to collaborate with other team members working with Golay pairs.

2.1.2 Adaptive Design of OFDM based on Ambiguity Function

Problem Description
In [8], we proposed an optimization procedure to select the OFDM waveform such that the volume of the corresponding wideband ambiguity function best approximates the volume of a desired ambiguity function.

Background
The conventional formulations of the ambiguity function either do not include a scattering coefficient of the target in the received signal model, or they assume identical values for the scattering coefficients corresponding to different directions and/or frequencies.

Progress
First, we developed a multi-carrier OFDM signal model and computed the corresponding wideband ambiguity function (WAF) at the output of the matched filter, including the effects of the target response on the received signal. Then, we devised an algorithm to adaptively design the spectrum of an OFDM signal such that the volume of the corresponding WAF best approximates that of a desired ambiguity function. Our numerical examples show that the optimization algorithm puts more signal energy at subcarriers in which the target response is weaker.

2.1.3 OFDM MIMO Design for Low-Angle Tracking Using Mutual Information

Problem Description
In [9], we proposed an optimization algorithm based on mutual information criterion to select the OFDM waveform of a co-located MIMO radar used for low-angle tracking.

Background
The conventional open-loop tracking systems do not integrate the waveform design technique with the tracking algorithm.

Progress
First, we developed a dynamic state model for the target, including the target position, velocity, and scattering coefficients of the target at different frequencies into the state vector, a parametric OFDM MIMO radar measurement model. Based on these models, we presented a sequential Monte Carlo method (particle filter) to track the target. Then, we proposed a new adaptive waveform design technique to maximize the mutual information of the target state and measurement vectors. Our numerical examples demonstrated the achieved performance improvement due to the adaptive waveform design.

2.1.4 Radar Waveforms with Ambiguity Functions Free of Sidelobes inside a Desired Range or Doppler Interval

Problem Description
To develop simple methods for constructing radar waveforms with ambiguity functions that are free of sidelobes inside a desired range or Doppler interval.

Background
Sixty years ago, efforts by Marcel Golay to improve the sensitivity of far infrared spectrometry led to the discovery of complementary sequences which have the property that the sum of their autocorrelation functions vanishes at all delays other than zero. Almost a decade after their invention, Welti rediscovered complementary sequences (there are his D-codes) and proposed to use them for pulsed radar. However, since then they have found very limited application in radar as it soon became evident that the perfect autocorrelation property of complementary sequences cannot be easily utilized in practice. The reason, to quote Ducoff and Tietjen, is "in a practical application, the two sequences must be separated in time, frequency, or polarization, which results in decorrelation of radar returns so that complete sidelobe cancellation may not occur. Hence they have not been widely used in pulse compression radars." Various generalizations of complementary sequences including multiple complementary codes by Tseng and Liu, and multiphase (or polyphase) complementary sequences by Sivaswami and by Frank suffer from the same problem.

These roadblocks served as the starting point our research program. We have described in [10],[11] how to design pulse trains for which the composite ambiguity function maintains ideal shape at small Doppler shifts. We have also described new nonlinear signal processing methods that enable use of complementary waveforms in OFDM radar and provide Doppler resilience at the chip level. Looking to the future, we have proposed unitary filter banks as a new illumination paradigm that enables broad waveform adaptability across time, space, frequency and polarization.

Progress
We have dualized in [12] the results reported in [10],[11] to design waveforms for which the ambiguity function is free of Doppler sidelobes across a range interval of interest. This was accomplished by exploiting the time-frequency duality between PAM and OFDM waveforms. The pulse trains designed in [10],[11] for range sidelobe suppression employ PTM sequences of Golay complementary codes to amplitude modulate a pulse shape in time. Depending on the choice of the PTM sequence, the resulting PAM waveform annihilates range sidelobes inside some Doppler interval. The new dual waveforms stack a PTM sequence of Golay complementary codes across OFDM tones to annihilate Doppler sidelobes in a range interval of interest. Sequential application of the two designs can be used to suppress range sidelobes and Doppler sidelobes in succession. The proposed designs are simple and only require a phase code library with two components that form a complementary pair.

2.1.5 Matched Segment Processing and Waveform Design for Enhanced Delay-Doppler Resolution

Problem Description
In this work, we consider the design of radar waveforms made of temporal segments that have low amplitude cross-ambiguity functions which can be used with a novel nonlinear processor to yield increased delay-Doppler resolution and sidelobe attenuation at the cost of a slight-to-modest reduction in detection performance.

Background
The novel nonlinear processor is based on models of neural processing in echolocating bats. A separate matched-filter Doppler filter bank is applied to each separate waveform segment, resulting in a separate delay-Doppler response map for each separate segment of the waveform. The delay-Doppler maps from each waveform segment are then combined using a family of nonlinear functions, resulting in a delay-Doppler response map with reduced ambiguity and enhanced resolution when compared to standard matched filter processing. We began this work last year and have significantly extended it this year.

Progress
In addition to the point-wise product matched filter processor we reported on last year, we have developed the point-wise minimum and point-wise blanking matched-segment processors as well during the last year. Both of these processors have significant improvement in multi-target artifacts, but they have a slight additional detection performance loss. We have analyzed the minimum processor it it has an additional detection performance loss of approximately 0.5 dB when compared to the product processor. The delay-Dopper response of the blanking processor looks slightly better than the minimum processor, but we are still analyzing its performance. The analysis of the blanking processor is much more difficult because of the adaptive nature of the nonlinearity.

We have show analyzed the response of all of these processors for two-segment V-chirp and twin-Costas sequence waveforms. In both cases, a significant decrease in ambiguity response occurs, with only slight artifacts in the multiple target case. We have also investigated additional coded waveform designs to be used with this approach.

These waveforms can be used with a standard matched filter receiver for detection, and then the nonlinear processor can be used for high-resolution delay-Doppler measurements when target discrimination and parameter estimation are required in the presence of interfering targets. Even when used for detection without preprocessing by a matched-filter receiver, it is shown that a loss of only 1–3 dB is incurred in detection performance, however there is a significant increase in delay-Doppler resolution and and decrease in delay-Doppler ambiguity.

2.1.6 Sampling Techniques for Low Ambiguity Waveforms by Adaptive Radon Transforms

Problem Description

The design of radar waveforms that have low ambiguity in both delay and Doppler is a classical problem in Radar signal design. We have focused on improving the resolution of the waveforms by using an adaptive Radon transform. A train of pulses with different ambiguity profile illuminates the target and the matched filtered returns are then radon transformed adaptively along preferred directions. Combining adaptive probing and processing can lead to improved resolution. The sequence of directions along which waveforms are chosen involves sampling the Radon space. Based on past samples, the optimal choice of future samples or waveform ambiguity profiles can be assessed. Finding optimal sequence of radon directions is an example problem of optimal sub-nyquist sampling of frequency sparse band limited signals, which exploits prior information on its frequency content and knowledge from the previous samples.

Background

There is a vast literature on the design of coded waveform trains that have improved delay-Doppler resolution. These include Barker sequences, Costas Sequences, Frank codes, etc. There is also recent literature on using nonlinear processing for improving the resolution of the radar returns. The subject of compressed sensing studies sampling of frequency sparse signals. There is significant work on minimum samples for reliable reconstructions. The problem of optimal sequence of samples based on prior knowledge on frequency content of the signal is not as well studied and is quite meaningful in the present context.

Progress

We have begun to study optimal sequence of coded waveforms and other transforms for enhancing delay Doppler resolution. We have proposed an algorithm [13] for deterministic sampling and reconstruction of sparse band-limited signals which exploits the prior frequency content of the signal and the sequence of collected samples. We are working on incorporating this to optimal waveform design by sequentially sampling of the Radon space.

Another important aspect of our work has been study of design of probe signals for system identification in MR spectroscopy [14] – [25]. Our work has led to design of novel radio frequency pulse sequences in liquid and solid state MR spectroscopy that provide superior signal to noise ratio than previously known state of the art methods. This work falls in our general research program in the MURI of using waveform design to make possible measurements which would not be otherwise accessible. In the last year, we have worked extensively on the design of amplitude and phase modulated pulse sequences, which helps to precisely estimate frequencies of spins of certain species in the presence of the other spins.

2.1.7 Unitary Waveform Design for MIMO Systems

Problem Description

In active sensing systems, the objective is to design a system that allows one to learn the environment, which could be one or more moving targets in the case of a radar. In a radar system, the transmitted waveforms are reflected by the target and the reflected returns are then processed at the receiving end to determine the location and speed of the target. The delay in the received waveforms corresponds to the distance of the target from the radar, and the doppler shift determines the speed at which the target is moving. Therefore, it is desired to transmit a waveform that provides good resolution in terms of the delay-doppler properties of the radar returns. Recently, there has been a lot of interest in MIMO radar after the success of MIMO in communications. MIMO radar offers superior performance over the conventional radar systems in that it provides multiple independent views of the target if the antennas are placed sufficiently far apart. In a MIMO radar, different transmit waveforms are transmitted from the transmitting antennas and the returns are then processed to determine the target presence, location and speed. The challenge in MIMO radar, amongst other things, is waveform separation at the receiver. To this end, a widely studied approach has been to transmit orthogonal waveforms that can be separated at the receiver. However, the relative delay and doppler shift of the transmitted waveforms generally destroys their orthogonality. Thus, we desire waveforms that remain orthogonal through a certain range of delay and doppler shifts. This problem has been the mainstay of a lot of recent work in the area of adaptive waveform design, which forms the basis of our current and future research.

Background

A multi-channel radar scheme was proposed in literature for a 2×2 system employing polarization diversity for getting multiple independent views of the target. In this scheme, Golay pairs of phase coded waveforms are used to provide synchronization, and Alamouti coding is used to co-ordinate transmission of these waveforms on the horizontal and vertical polarizations. The combination of Golay complementary sequences and Alamouti coding makes it possible to do radar ambiguity polarimetry on a pulse-by-pulse basis, which reduces the signal processing complexity as compared to distributed aperture radar. This scheme has been shown to provide the same detection performance as the single channel radar with significantly lower transmit energy or, alternatively provide detection over greater ranges with the same transmit energy as the single channel radar. However, this scheme dealt with a scenario in which the Doppler shift was assumed to be negligible, which is a rather simplified assumption in the context of radar. To address this issue, PTM sequences were used to make the Golay sequence transmissions resilient against Doppler shifts. The method achieves good results for small Doppler shifts, but the number of PRIs needed per transmission of the coded Golay sequence matrix is large, and thus require the radar channel to stay constant over large intervals of time, which is a rather restrictive assumption. Thus, a problem of interest is to design waveforms for more general MIMO radar systems that would allow for accurate target ranging in the presence of moderate to high Doppler.

Progress

In [26], we presented a more general framework for designing MIMO radar waveforms. The existing ideas were extended to more general symmetrical MIMO systems, and conditions for perfect waveform separation and reconstruction at the receiving end were derived. Examples of diversity waveforms for 2×2 and 4×4 systems were provided. In addition, new waveforms designs were proposed that allowed for both perfect separation and perfect reconstruction at the receiver. It was shown that Kronecker products of waveform sequences possess desirable properties that make them suitable for use in radar and active sensing applications. In the end, we introduced the problem of data dependent waveform design in which waveform designs were adapted according to the clutter and interference properties of the sensing environment. In [27], some of these ideas were used to develop a channel estimation technique for a MIMO-OFDM communication system, and it was shown that this technique would provide perfect channel estimates, in that the technique was only limited by the receiver noise.

The ideas developed in [26] were restricted to the cases where the Doppler shift was negligible. In [28], we developed a technique for accurate target ranging in the presence of Doppler using the unitary waveform designs of [26]. The technique is based on finding the null-space of the waveform matrix after multi-time-slot matched filtering at the receiver, and then using a vector from the null-space to process the matched filtered received waveform. We confirmed our theoretical analysis through simulations that show how our proposed technique minimizes the effects of Doppler and makes accurate target ranging possible over a wide range of Doppler shifts and target SNRs. In the future, we plan to provide a theoretical analysis of the detection performance, and extend this technique to situations where multiple targets are present in the same range cell. We are currently working on extending these ideas to cases where multiple targets are present, and developing an understanding of the resolution properties of these systems, along with possible ways to improve Delay-Doppler resolution.

2.2 Environment and Channel Modeling

2.2.1 Fringe Formulation (ITD+ Physical Optics Endpoints) to Augment Physical Optics

Problem Description
A wider class of propagation models can be analyzed using complex point sources (CPS). Antennas can be easily modeled and interactions with reflectors are computed as a superposition of effects of simpler radiators. A faster and less resource-consuming approach can be used to simulate reflector's behavior instead of the Method of Moments (MoM).

Background
Initial work on CPSs by Heyman led the way to an electromagnetic exact description of Gaussian Beams. The importance of CPSs lies on the fact that they can be used as basis functions for the expansion of more general radiated fields by any time of feed. CPSs have been considered in the Incremental Theory of Diffraction (ITD) as an extension in complex space of incremental field methods. For the case where no stationary-phase conditions exist in the analysis of reflectors (see parabolic reflector), an approach of PO and CPS ENDPOINT correction has never been taken into account.

Progress
The CPS expansion works and has been demonstrated for both planar and parabolic reflectors. The approach of physical optics (PO) + Incremental Fringe Formulation leads to results that are closer to what predicted by MoM [29], [30]. In the future we are expecting to compute also the incremental double diffraction coefficients.

2.2.2 Enhancing Radar Ambiguity

Problem Description
We consider and introduce the effect of the propagation environment into the analysis of the Ambiguity Function of radar signals. This analysis is based on a more complex expression of the hypothesized return signal because it includes more information regarding the behavior of the signal in the particular propagation medium.

Background
For monostatic radar scenarios, it is well understood that the ambiguity function naturally arises from the maximization of the output of a filter matched to the expected return signal, which is assumed to be measured in additive white Gaussian noise. In monostatic radars, the target return is parametrically expressed in terms of target's position and radial velocity. A simple receiver consisting of a matched filter and a threshold detector is commonly employed to estimate the target parameters, and the detector performance is then presented in terms of the ambiguity function. The same framework was extended to single transmit and single receive bistatic radar in existing literature, where the stress is on the importance of accounting for the geometry of the system (i.e. the locations of the two radars and the target) in the return signal model. In current literature, the previous approach was further extended to multistatic radar systems with a single transmitter and multiple receivers. This kind of analysis enable us determine the sensor positions for best radar performance.

Progress
In this work, we enhance the definition of Ambiguity Function by introducing the deterministic return signal hypothesized for the specific propagation environment involving radar and target. In this way, we will able to characterize the effects of radar-target environment as well as radar signal waveform, and radar geometry on the radar system performance in a more comprehensive way [31].

2.3 Target Detection

2.3.1 MIMO Radar Detection and Adaptive Design in Compound-Gaussian Clutter

Problem Description
We considered the target detection by multi-input multi-output (MIMO) radar systems with widely separated antennas in the presence of compound-Gaussian clutter. In [32], we adaptively distributed the total transmitted energy among the transmitting antennas.

Background
MIMO radars with widely separated transmitters and receivers are useful to detect a target in the clutter using the spatial diversity of the scatterers in the illuminated scene. Earlier work has addressed the detection problem in the presence of white and colored Gaussian noise. However, real clutter often deviates from the complex Gaussian model. Therefore, the conventional Gaussian model cannot represent the heavy-tailed clutter statistics that are distinctive of several scenarios, e.g., high-resolution and/or low-grazing-angle radars in the presence of sea or foliage clutter. Hence, in our model, we assumed compound-Gaussian clutter with the inverse gamma distributed texture components to fit such scenarios.

Progress
We addressed the problem under both high [32],[33] and low pulse-repetition frequencies (PRFs) [32]. First, we introduced a data model using the inverse gamma distribution to represent the clutter texture. Then, we applied the parameter-expanded expectation-maximization (PX-EM) algorithm to estimate the clutter texture and speckle as well as the target parameters. Using these estimates, we formulated a decision test based on the generalized likelihood ratio (GLR) and approximated its statistical characteristics. Based on this test, we proposed an algorithm to adaptively distribute the total transmitted energy among the transmitters increasing the probability of detection [32]. We demonstrated the advantages of MIMO and adaptive energy allocation using Monte Carlo simulations.

2.3.2 Polarimetric MIMO Radar with Distributed Antennas for Target Detection

Problem Description
In [34], [35], we addressed the problem of target detection for Multiple Input Multiple Output (MIMO) radar systems with widely separated antennas. Each of the transmit has the capability of transmitting waveforms of any arbitrary polarization. We also discussed the problem of optimal design of the transmit polarizations.

Background
MIMO radar systems with widely separated antennas enable viewing the target from different angles, thereby providing spatial diversity gain. Polarimetric design of the transmit waveforms based on the properties of the target scattering matrix provides better performance than transmitting waveforms with only fixed horizontal or vertical polarizations. In [34], [35], we proposed a radar system that combines the advantages of both systems by transmitting polarized waveforms from multiple distributed antennas, in order to detect a point-like stationary target.

Progress
In [34], [35], we considered the receive antennas of the proposed system use 2D vector sensors, each measuring the horizontal and vertical components of the received electric field separately. We designed the Neyman-Pearson detector for this proposed system and analyze its performance. This analysis was used to select the optimal transmit polarizations for this system. Using simulations, we demonstrated the improvement offered by the optimal choice of polarizations. We also demonstrated the advantages of retaining the 2D vector measurements without combining them.

2.3.3 Target Detection with Waveform Design in Rapidly-varying Radar Scenes

Problem description
For detecting targets in rapidly varying-radar scenes with improved performance, we developed an adaptive waveform algorithm that directly depends on the sea clutter statistics. The algorithm first estimates the sea clutter statistics when the signal-to-clutter ratio (SCR) is low, and then uses the estimated statistics to schedule the waveform to be transmitted at the next time burst.

Background
Although methods exist for improving the target detection performance in radar by optimizing the transmitted waveform under slowly-varying conditions, rapidly-varying clutter scenes are not well-studied. In last year's report, we developed a waveform-agile detection algorithm that depended on selecting the waveform parameters by maximizing the generalized maximum likelihood ratio detection test at the predicted target state.

Progress
Before designing the waveform, we track the scattering function of rapidly-varying sea clutter in low SCRs at each burst by estimating the clutter's space-time covariance matrix. Based on this estimated clutter statistics, we schedule the waveform to be transmitted in the next burst by minimizing the sea clutter influence. The waveform-agile target detection could be extended to include target tracking.

2.3.4 Urban Waveform-agile Detection and Multipath Exploitation

Problem description
We consider the problem of detecting a moving target in varying urban environment conditions, including multiple paths and complete loss of direct path. We employ both multipath exploitation and waveform design concepts to improve detection performance.

Background
Originally designed for operation in open, unobscured areas, radar systems have been widely used for detecting and tracking multiple targets in adverse conditions. As technology and warfare have progressed, however, the need has risen for a radar system capable of tracking targets in a dense, urban environment. However, in dense environments, most radars fail due to large and inconsistent returns from multiple distracting objects and obscuration.

Progress
We developed an algorithm to detect a vehicle moving in an urban terrain by exploiting multipath geometry and introducing waveform configuration to improve detection performance. In our simulation, a vehicle is moving around a loop in such a way that there is almost always at least one building adjacent to the vehicle. As a result, at different time steps, the stationary airborne radar has access to either only direct line-of-sight (LOS) or both one-bounce multipath and LOS or only one-bounce multipath or two-bounce multipath and LOS or only two-bounce multipath measurements. Simulations show that the multipath exploitation makes a difference in performance when LOS is not available. We are currently working on the waveform configuration to improve detection using simulated data in order to emulate a real scenario; our aim is to use waveform design to suppress the influence of clutter.

2.4 Target Tracking

2.4.1 Waveform-agile Target Tracking Using MIMO Radar

Problem description
We considered the problem of designing the transmit waveforms used by a multiple-input, multiple-output (MIMO) radar system for dynamic target tracking. The agile tracking algorithm developed is based on using the Cramér-Rao bound (CRB) to estimate the target position and velocity that can be represented in terms of the transmitted waveform parameters. The waveform-agile algorithm is formulated for both colocated MIMO radar and widely-separated MIMO radar systems.

Background
MIMO radars are increasing in popularity as they can provide more degrees of freedom, with regards to waveform design and diversity, when compared to phased-array radars, leading to improved system performance. Various studies were recently published discussing the MIMO radar ambiguity function and its relation to the CRB. However, estimating target tracking parameters in a dynamic scenario using waveform-agility is still a challenging research topic.

Progress
We developed waveform design algorithms for MIMO radar systems that track moving targets. Using the derived CRB at high signal-to-noise ratios (SNRs), we adaptively select the waveform parameters that minimize the predicted mean-squared tracking error at each time step. Using the assumption that the observation noise is approximated by the CRB when the SNR is high, the CRB predicts the tracker performance for waveforms with varying parameters which are then selected to minimize the trace of the predicted error covariance.

2.4.2 Waveform-agile Estimation Using MIMO Radar

Problem description
We addressed the problem of estimating the location of a stationary target using MIMO waveform-agile radars in our last year's report. At the time, we only used linear frequency-modulated (FM) chirps in the waveform parameter selection algorithm; we now also include a time-varying phase to be selected by the algorithm. The waveforms used are generalized FM chirps, and the algorithm selects the phase and duration of the signal in order to improve the maximum-likelihood estimation performance of the range and direction-of-arrival (DOA) of a target using MIMO radars with colocated antennas.

Background
Earlier work used the CRLB in MIMO radar applications to design a random transmission waveform according to the desired beam pattern. However, the CRLB for the joint range-DOA estimation was not used before to select transmit waveform parameters.

Progress
We configured generalized FM waveform parameters to minimize the trace of the predicted tracking error covariance by assuming that the covariance of the observation noise is approximated by the CRB at high SNRs. We optimally selected the duration and time-varying phase function parameters of generalized FM chirps to minimize the estimation mean-squared error under constraints of fixed transmission energy and constant time-bandwidth product.

2.4.3 Sensor Scheduling with Waveform-agility for MIMO Radar Target Tracking

Problem description
We developed algorithms for scheduling MIMO radar sensors (with widely-separated antennas) while designing transmit waveforms for optimal dynamic target tracking performance [36, 37]. We considered two scenarios: (a) scheduling sensors to minimize resource utilization, that is, the algorithm is designed to choose the minimum number of radar sensors such that the tracking mean-squared error (MSE) is below a specified threshold; and (b) scheduling sensors to minimize the predicted tracking MSE, that is, the algorithm activates only those radar sensors that result in minimizing the MSE, given a maximum number of available radar sensors.

Background
Sensor scheduling algorithms for multistatic radar systems have been previously considered in the literature. Application of these algorithms has particular advantages in a MIMO radar system because MIMO radars can provide multi-aspect measurements. In addition, considering waveform design for the radars that are scheduled to transmit can allow for further improvements in tracking performance.

Progress
We derived CRB to estimate target position and velocity based on the location of the widely-

separated MIMO radar sensors and the parameters of the transmit waveforms. For each of the scheduling algorithms, we formulated the scheduling problem as a mixed boolean-convex optimization and solved it using the branch and bound algorithm. We then integrated waveform design by minimizing the predicted tracking estimation MSE while adaptively selecting the transmit waveform parameters at each time step. We demonstrated the effectiveness of scheduling with waveform design in MIMO radar with both scheduling algorithms.

2.4.4 Urban Waveform-agile Tracking and Multipath Exploitation

Problem description
We consider the problem of waveform design to improve target tracking in urban environments. Unlike the urban detection problem discussed in Section 2.3.4, we concentrate only on tracking and waveform design, assuming perfect detection. We formulated the measurement equations in terms of the geometry-dependent multipath returns and related them to the unknown target position and velocity parameters. The resulting nonlinear dynamic model can be solved for the unknown target tracking parameters using a particle filter. The waveform design algorithm can be incorporated into the particle filter in order to improve the tracking performance.

Background
The shift of the traditional open area operation of radar systems into urban environment requires a sophisticated design of an urban terrain radar tracking system. Recent research has focused on modeling the radar covarage based on LOS and non-LOS (or multipath) propagations. While the advantages of multipath exploitation, such as higher visibility and area of coverage, has been demonstrated in the literature, the use of waveform design in these environments to improve tracking is yet to be explored.

Progress
We formulated a three-dimensional urban tracking model, based on the nonlinear measurement model (that uses the urban multipath geometry with different types of measurements at different times) and the state model (where the state is the target position and velocity). The target motion uses several maneuvers chosen at different time steps according to the interacting multiple model algorithm. With a particle filter tracker, we adapt the transmit waveform using the CRB to minimize the estimation MSE and improve performance [38]. Note that we use CAD (computer-aided design) to simulate the LOS and non-LOS regions based on the urban canyon geometry and the orientation of the radar.

2.5 Waveform Adaptivity in Communications

2.5.1 Waveform Adaptivity in Multi-antenna Wireless Communications

Problem Description
To investigate the value of waveform adaptivity in multi-antenna wireless communications.

Background
Advanced multi-antenna (MIMO) techniques are critical to realizing the spectrum efficiency targets of future wireless systems such as 3GPP LTE-Advanced (LTE-A), and a very simple version of MU-MIMO has become part of the LTE standard. A major barrier to widespread adoption is insufficient feedback of channel state information from the terminals to the base station. Feedback supports spatial separation of users through precoder selection and currently there is a need to develop more effective methods of realizing feedback that are compatible with the LTE standard.

Progress
The standard approach to the design of coding schemes for multiple antenna systems is based on optimizing diversity and coding gains. This geometric approach leads to remarkable examples, such as perfect space-time block codes, for which the complexity of Maximum Likelihood (ML) decoding is considerable. Code diversity is an alternative and complementary approach where a small number of feedback bits are used to select from a family of space-time codes. Different codes

lead to different induced channels at the receiver, where Channel State Information (CSI) is used to instruct the transmitter how to choose the code. This method of feedback provides gains associated with beamforming while minimizing the number of feedback bits. Thus code diversity can be viewed as the integration of space-time coding with a fixed set of beams. It complements the standard approach to code design by taking advantage of different (possibly equivalent) realizations of a particular code design.

We have shown [39] that feedback can be combined with sub-optimal low complexity decoding of the component codes to match ML decoding performance of any individual code in the family. It can also be combined with ML decoding of the component codes to improve performance beyond ML decoding performance of any individual code. We have demonstrated [40] that predicted performance gains based on instantaneous feedback are largely preserved when the feedback is based on long-range prediction of rapidly time-varying correlated fading channels. Simulations have been documented for two channel models; the first is the Jakes model where angles of arrival are uniformly distributed and the arrival rays have equal strengths, and the second is a model derived from a physical scattering environment where the parameters associated with the reflectors vary in time and the arrival rays have different strengths and non-symmetric arrival angles.

This project has led to collaborative research programs with Qualcomm, where Princeton graduate student Yiyue Wu is a 2009 summer intern, and with DOCOMO Euro Labs.

2.6 Compressive Sensing for DOA Estimation and Radar

2.6.1 Performance Analysis for Sparse Support Recovery

Problem Description
We analyzed the performance of estimating the common support for jointly sparse signals based on their projections onto lower-dimensional space [41], [42]. We derived both upper and lower bounds on the probability of error for support recovery assuming general measurement matrices, by using the Chernoff bound and Fanos inequality, respectively. The lower bound is readily applicable to derive the minimal number of samples needed for accurate direction of arrival (DOA) estimation for an algorithm based on sparse representation. When applied to Gaussian measurement ensembles, these bounds give necessary and sufficient conditions to guarantee a vanishing probability of error for majority realizations of the measurement matrix.

Background
The common support for jointly sparse signals has significant physical meanings in compressive sensing as well as other application areas of sparse signal processing (e.g. DOA estimation). However, the performance of such systems is usually measured in terms of L2-norm. Our study takes the probability of error for support estimation as an alternative performance measure, one that is natural and important in practice.

Progress
The developed bounds are useful to measure the performance of DOA estimation based on discretization. We are currently deriving and simplifying the expression of these bounds taking into account the special form of the measurement matrix. We are investigating the implications of these bounds on system and recovery algorithm design. We are also applying the minimum description length (MDL) principle to develop algorithms when the support size is unknown.

2.6.2 Feasibility of the Reconstruction of a Sparse Scattering Field

Problem Description
To investigate feasibility of the reconstruction of a sparse scattering field by compressive sensing.

Background
The theory of compressed sensing suggests that successful inversion of an image of the physical world (e.g., a radar/sonar return or a sensor array snapshot vector) for the source modes and amplitudes can be achieved at measurement dimensions far lower than what might be expected from the classical

theories of spectrum or modal analysis, provided that the image is sparse in an apriori known basis. For imaging problems in passive and active radar and sonar, this basis is usually taken to be a DFT basis. The compressed sensing measurements are then inverted using an l1-minimization principle (basis pursuit) for the nonzero source amplitudes. This seems to make compressed sensing an ideal image inversion principle for high resolution modal analysis.

Progress
We have developed [43] an approach to radar imaging that exploits sparsity in the matched filter domain to enable high resolution imaging of targets in delay and Doppler. The starting point is a sparse representation for the vector of radar cross-ambiguity values at any fixed test delay cell in a Vandermonde frame that is obtained by discretizing the Doppler axis. The expansion coefficients are given by the auto-correlation functions of the transmitted waveforms. Orthogonal matching pursuit (OMP) algorithm is then used to identify the locations of the radar targets in delay and Doppler. Unambiguous imaging in delay is enabled by transmission of a Golay pair of phase coded waveforms to eliminate delay sidelobe effects. We have extended this work to multi-channel radar, by developing a sparse recovery approach for dually-polarimetric radar. Here sparsity is exploited in a bank of matched filters, each of which is matched to an entry of an Alamouti matrix of Golay waveforms to recover a co-polar or cross-polar polarization scattering component.

Now in reality no physical field is sparse in the DFT basis or in an apriori known basis. In fact the main goal in image inversion is to identify the modal structure. No matter how finely we grid the parameter space the sources may not lie in the center of the grid cells and there is always mismatch between the assumed and the actual bases for sparsity. We have studied [44] the sensitivity of basis pursuit to mismatch between the assumed and the actual sparsity bases and compared the performance of basis pursuit with that of classical image inversion. Our mathematical analysis and numerical examples show that the performance of basis pursuit degrades considerably in the presence of mismatch, and they suggest that the use of compressed sensing as a modal analysis principle requires more consideration and refinement, at least for the problem sizes common to radar/sonar.

This collaboration has been enhanced by a very successful summer internship of Princeton graduate student Yuejie Chi at Colorado State University. Two journal papers are in preparation for submission to IEEE Transactions on Signal Processing and IEEE Transactions on Information Theory.

2.7 Through the Wall Radar

2.7.1 An approach to estimating building layouts using radar and jump-diffusion algorithm

Problem Description
In [45], we addressed the problem of estimating building layouts using exterior electromagnetic sensing, which is important in urban warfare. Solving this problem is challenging due to the complex and unknown environment. At the same time, inner walls have some a priori known information that would be useful to utilize.

Background
Reconstruction of the building layout belongs to the broad area of inverse scattering. Procedures for solving inverse scattering problems can be classified into deterministic and stochastic.iterations. We used the stochastic algorithm that enables efficient inclusion of the prior knowledgethe jump-diffusion algorithm

Progress
In [45], we proposed using the jump-diffusion algorithm as a powerful stochastic tool that can be used to estimate the number of walls, their unknown positions and other parameters. We develop an efficient iterative procedure that first uses low-frequency transmissions to obtain rough estimates of the building layout. These estimates are then used to initialize the estimation at higher frequencies, thus obtaining more accurate results. We showed that with proper frequency selection, the building layout can be estimated using radar measurements at only a few frequencies. Numerical examples

are used to illustrate the performance of the proposed algorithm in practical situations.

2.7.2 Estimating moving targets behind reinforced walls using radar

Problem Description
In [46], we considered the estimation of moving targets located behind concrete walls reinforced with metallic bars, using radar measurements. The periodic structure of the rebar severely attenuates and distorts transmitted waveforms, which produces defocused images with ghost target estimates.

Background
An important task in urban warfare is using exterior electromagnetic sensing to detect people hidden inside buildings. The walls significantly attenuate and distort transmitted signals; hence electromagnetic modeling has an important influence on estimation accuracy. The distortion is particularly prominent in the case of walls reinforced by parallel steel bars (rods) or square-grid meshes, which are commonly used in construction.

Progress
In [46], we applied beamforming to estimate permittivity and thickness of the wall and number and position of the targets. The proposed solution is based on accurate physical models calculated using the method of moments. We showed that the estimation is significantly improved by modeling the waveform distortion due to the bars. The resulting images are focused and clearly represent the contours of the targets. The algorithm is robust to the ambiguities in bar parameter values. In addition, the minimal necessary SNR is lower compared with the case in which the influence of the bars on the signal shape is ignored.

2.7.3 Exploiting multipath from airborne platforms for improved direction of arrival estimation

Problem Description
In the direction-of-arrival estimation, the scattering of the incident signal from airborne platforms is often neglected or considered as clutter. However, these additional signal paths, mostly due to the diffraction from the platform wedges, contain useful information about the incoming waves. Recent research showed that the waves reflected from the known objects surrounding the target improve the accuracy of the target estimation or image. We show that similar improvement is obtained if the antenna array interaction with the hosting platform is taken into the account.

Background
Radars often receive multipath signals from the target due to the reflections from the objects close to the target. Several studies show that the target localization is improved if the reflections from water, land, or surrounding buildings are taken into account. Additional signal paths increase the radar coverage, especially when there is no optical visibility between the radar and the target.

Progress
In [47], [48] we incorporated the multipath into the signal processing algorithms, and study the improvement by computing the Cramer-Rao bound. We showed that the exploitation of the multipath from the sensor platforms significantly improves the estimation of the unknown incident signals. Moreover, the capacity to resolve multiple signals is enhanced.

2.7.4 RF Tomography: Underground Void Detection

Problem Description
The problem of underground void detection is paramount to secure borders, sensitive areas, and for search and rescue missions.

Background
To date, no underground imaging technique emerged as a standard for close-in sensing of wide denied areas, where minimal human intervention is required.

Progress
A promising strategy is introduced in [49], [50] where one set of transmitters (Tx) and one set of receivers (Rx) are placed on (or in) the ground at arbitrary positions. The transmitters (Tx) radiate a monochromatic signal, which impinges upon a buried dielectric or conductive anomaly, thus generating a scattered wave. Multiple receivers collect samples of the scattered electric field, and relay this information to a base station. Images of the below-ground scene are then reconstructed using the principles of RF Tomography. Advantages and mathematical derivations of RF tomography for underground imaging are discussed in [49]. The approach is technically valid for any sensor disposition and terrain shape, provided that the Green's function characterizing the problem is properly selected. In [49] the Green's function for a homogeneous space was applied, due to its simplicity of implementation. This choice has been proven to work satisfactorily when the sensors are located nearly vertically above the targets, thus avoiding artifacts due to the discontinuity at the air-earth interface. However, practical applications require wide areas of investigations (e.g. underground networks and facilities), denied areas (e.g. sensing of urban environment) or close-in sensing (e.g. covert missions). In these cases, sensors remotely probe underground regions at long ranges, and the propagation of waves occurs primarily along the air/ground interface; hence, the predominant propagation mode is the lateral wave. Therefore, one contribution of this work is the introduction of a more accurate forward model by invoking a closed form Green's function that accounts for the air-earth discontinuity [50].

2.8 Other Published Work

References [71]-[96] are of papers we published during the time period of this report. However, since we have already mentioned the same work in our last report, we do not repeat it here.

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Contents

1 Rationale **2**

2 Research **2**

2.1 Waveform Diversity and Design 2
2.1.1 Pulse-Doppler Radar Using Nonuniform Coherent Pulse Trains 2
2.1.2 Ambiguity Function Analysis 2
2.1.3 Biologically Inspired Coupled Antenna Array Design 3
2.1.4 PQ Sequences and Sidelobe Suppression 4
2.1.5 Exploiting Doppler with MIMO Unitary Waveforms 5
2.1.6 Tailoring Ambiguity Functions 5
2.2 Environment and Channel Modeling 6
2.2.1 Underwater Communications Channel Modeling 6
2.2.2 Incremental Double Edge Diffraction for Complex Source Point Illumination 6
2.3 Target Detection 7
2.3.1 Computationally-Efficient Robust Multiscale CFAR Using Empirical Distribution Functions 7
2.3.2 MIMO Radar Detection Under Phase Synchronization Errors 8
2.3.3 Slow-Time Multi-Frequency Radar for Target Detection 8
2.3.4 Passive Radar for Target Detection 9
2.4 Target Tracking 9
2.4.1 Monopulse MIMO Radar for Target Tracking 9
2.4.2 Cognitive Radar for Target Tracking in Multipath Scenarios 10
2.4.3 Sparsity-Based Multi-Target Tracking Using OFDM Radar 10
2.4.4 Urban Tracking with Waveform Design in High Clutter 11
2.4.5 Tracking Using Waveform Design for MIMO Urban Radar 11
2.4.6 Track-Before-Detect Multipath Exploitation Radar 12
2.5 Compressive Sensing for DOA Estimation and Radar 12
2.5.1 Compressive Sensing for MIMO Radar with Widely Separated Antennas 12
2.5.2 Electromagnetic Imaging Using Compressive Sensing 13
2.5.3 Computable Quantification of the Stability of Sparse Signal Reconstruction 13
2.5.4 Stability of Low-rank Matrix Reconstruction 14
2.6 RF Tomography 14
2.6.1 Underground Void Detection 14
2.7 Other Published Work 15

1 Rationale

In this project, we develop methods for adaptive design of signals transmitted by radar or communication systems. Such methods are aimed to optimize the performance in the presence of time-varying environmental conditions and, in the case of radar, respond to unknown parameters of static and dynamic targets. We devise algorithms that exploit the waveform diversities in multiple dimensions, such as time, space, frequency, phase, power, and polarization. We demonstrate, thorough analysis, that our proposed methods provide dramatically improved performance over existing systems.

In the last year we made significant progress in various aspects, including waveform design, environment modeling, algorithms for target detection and tracking, waveform adaptivity in communications, compressive sensing and through-the-wall radar. Our contributions reflect the multidisciplinary subjects of the project and composition of our team. Namely, we have experts in mathematics, statistics, engineering, and physics. The research of the team members span the areas of signal processing, radar, electromagnetics, information theory and communications. In the following, we summarize in more detail our recent achievements.

2 Research

2.1 Waveform Diversity and Design

2.1.1 Pulse-Doppler Radar Using Nonuniform Coherent Pulse Trains

Problem Description
A uniformly spaced coherent train of pulses is commonly used in radar systems for improving Doppler resolution. In traditional coherent pulse radars, a basic pulse with good autocorrelation properties is chosen and transmitted periodically at a certain pulse repetition frequency (PRF). The received echoes are then processed coherently. Transmitting same signal periodically and then processing the returns coherently introduces large ambiguities in the matched filter delay-Doppler response, or the pulse train ambiguity function, which occur at multiples of pulse repetition interval along the delay axis and at multiples of PRF along Doppler axis. This necessitates a design choice to be made since decreasing PRF would result in longer delay range but will impact Doppler resolution. Pulse Doppler radars are classified as low or high PRF radars, depending on the choice made during the system design.

Background
Different parameters of the pulse train can be varied to optimize the ambiguity function and trade resolution properties. Common variations, leaving aside the amplitude weighting, include phase coding of individual pulses or employment of diverse pulses to decrease correlation. One simple technique that has not been used as commonly is to stagger the pulses in the pulse train. Pulse staggering is not a new idea and it is known that pulse staggering can 'break up' the 'bed of nails' delay-Doppler response of uniform pulse trains. However, the lack of uniformity in pulse spacing makes it impossible to use the standard DFT-based pulse-Doppler processing architecture. For this reason, pulse-staggering has not been used in coherent pulse-Doppler radars.

Progress
We have developed a DFT based pulse Doppler processing receiver for staggered pulse trains [1], [2]. The proposed receiver is a simple extension of traditional DFT based coherent pulse train processing. We show that P DFT processors are required to process the staggered train of pulses as a coherent signal, where P is the number of available pulse positions in each pulse repetition interval (PRI). Thus the complexity of the processing hardware only increases linearly with the number of available positions. We have also investigated the distribution of ambiguity volume in the delay-Doppler plane as a function of the pulse positions and the selection of pulse shapes.

2.1.2 Ambiguity Function Analysis

Problem Description
We are investigating the vector-valued version of this problem because of MIMO and multi-sensor environ-

ments. This leads naturally to developing the theory of vector-valued discrete Fourier transforms (DFT).

Background
In the previous report, we described our ongoing research into the finer structure and construction of complex valued constant amplitude zero auto-correlation (CAZAC) sequences, and the behavior of the narrow band and wide band ambiguity functions of the phase coded waveforms whose coefficients are such sequences.

Progress
Our CAZAC software continues to expand, especially this year when we are finally understanding the role of algebraic geometry in the construction of CAZACs [3] and the profound algebraic backgound for non-quadratics CAZACs such as the Bjorck CAZACs which we continue to analyze [4]. Besides this available software, we have begun the new site, Collected Repository of Waveform Design & Software (CRoWDS) [5]. Much of our material for CRoWDS is collected but not yet available on the site. [6] has expanded significantly, and we have established a connection between infinite CAZAC sequences and a notion which we call multiplicative multi-resolution analysis (MRA). It is analogous to wavelet based MRA, but translation is replaced by multiplication in an operation transporting the action of increasing discrete subgroups of the real line. With regard to wavelets, we are continuing our point of view of analyzing $L2(R^d)$, d large, in terms of a single wavelet, while still retaining a zooming property of something like dyadic wavelets, as opposed to some single wavelets for $L2(R^d)$ whose generating filters are non-separable, see [7] for our latest results and point of view.

With regard to the vector valued theory, there have been two directions. The first is to extend the domain from the integers mod N to groups of matrices. The second has been our emerging understanding of the role of uncertainty principle inequalities, such as those of Candes and Tao. This has led to our approach of tying our theory together with the theory of compressive sensing, but in a deterministic way, see [8]. [6] has led us to view infinite CAZAC sequences as a means of developing an analogue-theory analogous to the means in which classical finite quadrature mirror filters are use in wavelet theory.

2.1.3 Biologically Inspired Coupled Antenna Array Design

Problem Description
In [9], [10], [11] and [12] we considered the design of a small-size antenna array inspired by the Ormia ochracea's coupled ears. In [9] and [10] we focused on the passive antenna arrays having high direction of arrival (DOA) estimation performance, and in [11] and [12] we designed the beampattern of an active antenna array with high radiation performance. Such small-sized arrays are essential in many tactical and mobile applications where the sensing systems are confined to small spaces.

Background
Accurate source localization in many civil and military applications require array of sensors (antennas) with high resolution, direction of arrival estimation accuracy and high radiation performance. The performance of the array is directly proportional to the size of the array's electrical aperture, such that large-aperture arrays are required to achieve better localization performance. However, using a large aperture array to improve performance can be costly also may not be feasible, since in many tactical and mobile applications the sensing systems are confined to small spaces, requiring small-sized arrays. The solution to this dilemma could be inspired by the nature, namely by a parasitoid tachinid fly called Ormia ochracea. To perpetuate its species, a female Ormia ochracea must find a male field cricket using the cricket's mating call. The female Ormia has a remarkable ability to locate these crickets very accurately using binaural (two-ear) cues (interaural differences in intensity and arrival time from an incident acoustic wave). This is unexpected due to the significant mismatch between the wavelength of the cricket's call (about 7 cm) and the distance between the fly's ears (about 1.2 mm) which gives rise to cues that are extremely small to be detectable by the central nervous system of the fly. Experimental research explains that the Ormia's localization ability arises from a mechanical coupling between its ears, which is simply modeled by a set of differential equations.

Progress
In [9] and [10], we developed a biologically inspired coupled passive antenna array. We solved the second order differential equations governing the Ormia's coupled ear response, and then converted this response to fit the desired radio frequencies. Using the converted response, we implemented the biologically inspired coupling (BIC) as a multi-input multi-output filter and obtained the desired array response of a uniform linear array

(ULA) with BIC. We derived the maximum likelihood estimates (MLEs) of the DOAs and computed the Cramér-Rao bound (CRB) on the DOA estimation error to analyze the estimation accuracy performance. We proposed an algorithm for the optimum BIC selection to maximize the localization accuracy. We extended our analysis to circular antenna arrays and computed the CRB on three-dimensional DOA estimation. Using Monte Carlo numerical examples, we compared the biologically inspired coupled antenna array with a standard one, and demonstrated the improvement in the estimation performance due to the BIC.

In [11] and [12], we designed the radiation pattern of a biologically inspired coupled transmission antenna array. We solved the differential equations governing the Ormia ochracea's ear response, and converted the response to the pre-specified radio frequencies. We then considered the converted response of the biological coupling in the array factor of a uniform linear array composed of finite-length dipole antennas, and also included the undesired electromagnetic coupling due to the proximity of the elements. We proposed an algorithm to optimally choose the BIC for maximum array performance. In our numerical examples, we computed the radiation intensity of the designed system for binomial and ordinary end-fire arrays, and demonstrated the improvement in the half-power beamwidth, sidelobe suppression, and directivity of the radiation pattern due to the BIC.

2.1.4 PQ Sequences and Sidelobe Suppression

Problem Description
To develop simple methods for constructing radar waveforms with ambiguity functions that are free of sidelobes inside a desired range or Doppler interval [13], [14].

Background
Sixty years ago, efforts by Marcel Golay to improve the sensitivity of far infrared spectrometry led to the discovery of complementary sequences which have the property that the sum of their autocorrelation functions vanishes at all delays other than zero. Almost a decade after their invention, Welti rediscovered complementary sequences (there are his D-codes) and proposed to use them for pulsed radar. However, since then they have found very limited application in radar as it soon became evident that the perfect autocorrelation property of complementary sequences cannot be easily utilized in practice. The reason, to quote Ducoff and Tietjen, is "in a practical application, the two sequences must be separated in time, frequency, or polarization, which results in decorrelation of radar returns so that complete sidelobe cancellation may not occur. Hence they have not been widely used in pulse compression radars." Various generalizations of complementary sequences including multiple complementary codes by Tseng and Liu, and multiphase (or polyphase) complementary sequences by Sivaswami and by Frank suffer from the same problem.

These roadblocks served as the starting point our research program. We have previously described how to design pulse trains for which the composite ambiguity function maintains ideal shape at small Doppler shifts. We have also described new nonlinear signal processing methods that enable use of complementary waveforms in OFDM radar and provide Doppler resilience at the chip level.

Progress
We have shown that the freedom to sequence a pair of Golay complementary waveforms in time makes it possible to design Doppler resilient pulse trains for which the composite ambiguity function maintains ideal shape inside a desired Doppler interval. This provides a solution for a long standing problem in active sensing, associated with the sensitivity of complementary waveforms to Doppler shift, which has limited the application of these intriguing waveforms for high resolution infrared, radar, and ultrasound imaging for almost sixty years.

The new idea, called PQ sequencing, is to use a binary sequence P to coordinate the transmission of a complementary pair of phase coded waveforms in time, and a binomial sequence Q to balance terms at the receiver. The key property is that the spectrum of the PQ sequence controls the size of the range sidelobes. By shaping the spectrum of the sequence around a Doppler frequency of interest we clear out range sidelobes of the ambiguity function within a desired Doppler interval. The key feature of this approach is its simplicity. The pulse train is constructed from only two phase coded waveforms and hence the waveform generators required at the transmitter can be considerably simpler than those required in waveform agile systems that exercise a large waveform library. We have also extended this design principle to multi-channel active sensing where we have designed PQ sequences of unitary filter banks which maintain their paraunitary property in presence of unknown Doppler effects.

2.1.5 Exploiting Doppler with MIMO Unitary Waveforms

Problem Description
Our objective is simultaneous transmission of multiple waveforms from different emitters, in such a way that processing the returns is as simple as possible. Technically we require that the overall ambiguity function is a sum of individual ambiguity functions which implies that their sum better approximates the ideal thumbtack shape [15]–[21].

Background
We have described a unitary design for the illustrative 4x4 example that prescribes the scheduling of the waveforms over four transmit antennas and over four PRIs. Matched filtering and combining of the returns over four PRIs has been shown to achieve both perfect separation (of the superimposed returns) AND perfect reconstruction. Perfect reconstruction implies that the sum of the time-autocorrelations associated with each of the four waveforms is a delta function. The net result is that the processing of four antennas over four PRIs yields 16 cross-correlations, all of which ideally exhibit a sharp peak at each target delay. Conditions for both perfect separation and perfect reconstruction have been developed, and a variety of unitary waveform sets satisfying both have been designed.

Progress
We have developed an alternative scheme for dealing with Doppler, based on a data-dependent weighting of the different PRI matched-filtered outputs prior to summing. In this approach, the target Doppler is used as an additional discriminant, as in MTI radar for example. There are no restrictions on the value of the PRI-to-PRI phase shift due to Doppler. Simulations have been conducted verifying the efficacy of the proposed unitary waveform matrix designs in conjunction with the proposed Doppler compensation technique. Applications of unitary waveform design to MIMO-OFDM wireless communications are also under development.

2.1.6 Tailoring Ambiguity Functions

Problem Description
The design of radar waveforms that have low ambiguity in both delay and Doppler is a classical problem in Radar signal design. We formulated the problem of design of waveforms with low ambiguity in delay and doppler as an fourth order optimization problem.

Background
A waveform is sequence of amplitude and phases, represented as a complex vector. Delay and Doppler shifts of the waveform are represented though Shift matrices acting on the waveform vector or its Discrete Fourier transform. Low ambiguity in the delay and Doppler can be formulated as low inner product between the original waveform vector and its transformation through various shift operators.

Progress
We showed through simulations that simple gradient descent on the amplitude and phases of the waveform converges to interesting looking waveforms with good ambiguity profiles. Future work will focus on understanding in detail this class of optimization problems and computational methods for searching for global optimal solutions to these problems. We have carried out some analysis on optimal sequence of linear measurements in Gausssian noise for estimating signal parameters. This is inspired by our recent work on low ambiquity waveforms by adaptive Radon transforms. We have developed the method of multiple rotating frame as a technique to design multiply modulated waveforms in magnetic resonance, which are immune to spread in natural frequencies of spins and hence have full spectral dominance. Theoretical foundations and various applications of this seemingly very powerful method is being explored.

2.2 Environment and Channel Modeling

2.2.1 Underwater Communications Channel Modeling

Problem Description
We investigate the problem of estimating the characteristics of underwater communication channels that represent the transmitted acoustic signals in terms of multiple time-delay and multiple Doppler scale path propagations. The channel characteristic estimation must lead to communication performance improvements over existing underwater acoustic processing systems.

Background
Characterizing underwater acoustic signal propagation is essential for many underwater signal processing applications, including underwater acoustic communications, active and passive sonar, and underwater navigation and tracking. The highly time-varying nature of the underwater environment can cause many undesirable distortions to the propagating signal. The time-varying multipath distortions may be the result of dense reflections from rough surfaces, fluctuations in sound speed due to inhomogeneous mediums, or relative motion not only between transmitters and receivers but also the propagating medium itself. Depending on the transmission frequency and the ocean depth, the resulting time-variation in the signal's spectral characteristics can be Doppler scaling (compressions or expansions) or dispersive (nonlinear) transformations. In particular, medium-to-high frequency (0.3-20 kHz) underwater acoustic signals are characterized by spreading caused by multiple time-delay paths and multiple Doppler-scaling paths. As the narrowband linear time-varying model is no longer suitable to describe these signal transformations, the matched wideband linear time-varying model should be used for more effective processing.

Progress
We investigated two approaches for characterizing wideband channels for underwater communications using medium-to-high frequency acoustic signals. Following a linear time-varying wideband system representation, we proposed two methods for estimating underwater communication environments [22]–[26]. The first method is based on estimating the coefficients of the discrete wideband spreading function from a canonical time-scale system representation. This is achieved by first detecting and separating major ray groups by applying a warping based filtering technique in the wideband ambiguity function lag-Doppler plane and then estimating the coefficients corresponding to each ray group using a least-squares approach. The second method follows a ray system model and estimates a highly-localized wideband spreading function using the matching pursuit decomposition algorithm by extracting time-scale features for different ray paths. As the channel is assumed sparse, we could have also used compressive sensing to perform the estimation, as we have previously done. We validated and compared both proposed methods using real communication data from the underwater BASE07 and KAM08 experiments. The BASE07 experiment was jointly conducted by the NATO Undersea Research Center (NURC), the Forschungsanstalt der Bundeswehr fur Wasserschall und Geophysik (FWG), the Applied Research Laboratory (ARL), and the Service Hydrographique et Ocanographique de la Marine (SHOM). The KAM08 experiment was conducted in shallow water off the western coast of Kauai, Hawaii, in June 2008. By using a matched channel model, we achieved a higher processing performance than when adopting techniques that can only compensate for the wideband effect.

2.2.2 Incremental Double Edge Diffraction for Complex Source Point Illumination

Problem Description
Ray tracing methods may be used to compute the electromagnetic fields scattered by electrically large structures. When these structures contain interacting edges, special care must be taken to correctly compute the fields. Interacting edges may be accounted for with double-diffraction coefficients. Specifically, we developed a high-frequency asymptotic Incremental Double Diffraction formulation that gives the correction terms for the fields diffracted by metallic reflectors when illuminated by Complex Source Points.

Background
Complex structures generally include multiple interacting edges and contributions involving fields of doubly diffracted rays by any two interacting edges need to be introduced to improve the field estimate. In fact, in several actual scattering and diffraction problems, the dominant field of a singly-diffracted ray is shadowed by a second edge, or is close to the shadowing region. The introduction of a double diffraction field becomes

necessary to compensate for such a discontinuity, mostly at grazing incidence and observation aspects. It is well known that the consecutive application of ordinary uniform theory of diffraction (UTD) coefficients fails when the edge of the second wedge lies within the transition region of the field diffracted by the first wedge. This occurs due to the rapid spatial variation and to the non ray-optical behavior of the field diffract ed by the first edge, which impinges on and illuminates the second wedge. The same limitation affects also the Incremental Theory of Diffraction (ITD) representation, thus preventing a simple subsequent application of the coefficients for single diffraction.

Progress
We developed a double diffraction coefficient which uniformly accounts for the different transitions that may occur. In some UTD formulations available in the literature, these coefficients are derived by solving a proper canonical problem. A similar procedure is formulated here for the incremental double diffraction problem applied to Complex Source Points. The problem is solved for the general case of the double diffraction between a pair of skewed separate wedges; nevertheless, the same concepts hold for the double diffraction between the edges of joined wedges that share a common PEC face. In both cases, the formulation provides an accurate, first-order asymptotic description of the interaction between the edges by introducing an augmented incremental slope diffracted field. The ITD representation for the incremental double diffraction field (ITD-DD) requires a two-fold numerical integration in the space domain on each edge of the complex structure.

Preliminary results for the double diffraction coefficients were presented in [27, 28], while related work on complex source points were given in [29].

2.3 Target Detection

2.3.1 Computationally-Efficient Robust Multiscale CFAR Using Empirical Distribution Functions

Problem Description
In this work, we develop a CFAR algorithm that combines multiresolution and order statistic techniques (implicitly through the use of empirical distribution functions) for adaptive reference window selection. One particular benefits of the technique is computational efficiency because the cell under test does not have to be accounted for in setting up the reference window because of the robustness of the order statistic techniques used. For this reason, we call this algorithm Cell-under-test Inclusive CFAR (CI-CFAR.)

Background
Optimal radar detection in clutter requires appropriate selection of the detector threshold. When clutter and noise statistics are fixed and known, a fixed threshold can be determined to achieve optimal performance. However, in clutter environments with unknown or changing statistics, the threshold selection problem is more difficult. One common approach to threshold selection in this case is to estimate the clutter statistics from resolution cells surrounding the resolution cell under test. The implicit assumptions in this approach are that the resolution cells used to estimate the clutter statistics are target free and the clutter returns from these cells are statistically representative of the clutter statistics of the cell under test. When either of these two assumptions is violated, the threshold computed using this approach may result in a significant degradation of detector performance, either in the form of a higher probability of false alarm or a lower probability of target detection.

In radar detection problems, detection thresholds are usually selected to maximize the probability of target detection while holding the false alarm constant. So the standard approach to adaptive threshold selection is to estimate a threshold value based on the radar returns from resolution cells surrounding the cell under test that will yield a constant probability of false alarm. The algorithms used to compute these adaptive thresholds are called Constant False Alarm Rate (CFAR) algorithms.

In implementing CFAR algorithms, a decision must be made as to how large a collection of reference cells should be used to estimate the detection threshold. This region is called the reference window. If the clutter statistics are homogeneous across all resolution cells in a neighborhood surrounding the cell under test, then using a larger reference window will result in more accurate estimates of the clutter statistics and a corresponding improvement in detector performance. However, if there is significant spatial variation—and hence nonhomogeneous statistical behavior—in the neighborhood surrounding the cell under test, selecting too large a reference window will result in inaccurate estimates of the clutter statistics and the corresponding detection threshold will not be well matched to the cell under test. For this reason, selection of the reference window size and region is an important consideration in designing CFAR detectors. Furthermore, because a particular radar scene may include large homogeneous regions as well as regions with significant inhomogeneity, it may not be the case that one reference window size is appropriate across the whole radar scene. For this reason, approaches to the adaptive selection of reference windows are of interest. Multiresolution techniques provide one possible approach to measuring the variation in clutter statistics on different spatial scales, and this information can be used to adaptively select reference windows.

In real radar scenes, another issue we consider is that as the size of the reference window increases, the likelihood that one or more of the reference cells contains a target also increases. Since the presence of interfering targets tends to increase the average radar return from the resolution cells containing these targets, order statistic based techniques can provide robust threshold selection having significant immunity to a small number of interfering targets in the reference window.

Progress
We have developed the multiscale CI-CFAR algorithm and compared its performance to CA-CFAR and OS-CFAR in a number of different nonhomogeneous clutter scenarios with and without interfering targets [30]. We have shown a significant increase in performance for a broad range of scenarios. We have also analyzed the computational complexity of the algorithm and shown that both the CUT-Inclusive property and the multiscale merging of previously ranked data results in a significant computational savings over traditional adaptive threshold techniques.

2.3.2 MIMO Radar Detection Under Phase Synchronization Errors

Problem Description
In [31], [32], we considered the problem of target detection for multi-input multi-output (MIMO) radar with widely separated antennas in the presence of a phase synchronization mismatch between the transmitter and receiver pairs. Such mismatch often occurs due to imperfect knowledge of the locations and local oscillator characteristics of the antennas.

Background
The advantage of MIMO radar with widely separated antennas is the ability to jointly process the multistatic data provided by multiple views of the target from different angles. Therefore, discrimination of the data due to different transmitters plays an important role in this procedure. Hence, signals with no or low cross-correlation properties for any Doppler shift and time delay are desired. However, since the waveform separation is limited by the Doppler and delay resolution, perfect signal separation is very difficult to achieve in practice. Moreover, time and phase synchronization may not be feasible in a MIMO configuration with airborne radars. The work on MIMO radar with widely separated antennas neglect these two effects.

Progress
We formulated the MIMO measurement model, including the cross-correlation and phase error terms. We assumed the cross-correlation terms are deterministic unknown and the phase errors follow von Mises distribution as a generalization of uniform distribution. We considered homogeneous clutter and introduce our parametric model under generalized multivariate analysis of variance (GMANOVA) framework. We applied expectation and maximization (EM) algorithm to estimate the target, error and clutter parameters. We developed a generalized likelihood ratio test using these estimates. Based on the mutual information between the radar measurements and received target returns (and hence the phase error), we proposed an algorithm to adaptively distribute the total transmitted energy among the transmitters. Using Monte Carlo simulations, we demonstrated that the adaptive energy allocation, increase in the phase information, and realistic measurement modeling improve the detection performance.

2.3.3 Slow-Time Multi-Frequency Radar for Target Detection

Problem Description
In [33], we proposed a method to detect a target in the presence of multipath reflections, employing sequential transmission of multiple frequencies in a slow-time (pulse-to-pulse) approach.

Background
To resolve and exploit the multipath components, it is common to use the wideband signals, an example of which is the orthogonal frequency division multiplexing (OFDM) signalling scheme. However, OFDM has not so widely been studied by the radar community because of its time-varying envelope which originates a potentially high peak-to-average power ratio (PAPR). Over the years a number of approaches have been proposed to reduce the PAPR problem, and most these techniques suggest modifications to the OFDM signal over "fast time" (within a pulse). Instead, here we propose to use a "slow-time" (pulse-to-pulse) approach in which only one of subcarriers (which certainly has constant envelope) is employed over a particular pulse.

Progress
First, we developed the measurement model that accounts for the specular multipath reflections as well as Doppler shifts, under the generalized multivariate analysis of variance (GMANOVA) framework. Then, we formulated the detection problem and employed the generalized likelihood ratio (GLR) test. We analytically evaluated the performance the GLR test statistics under both hypotheses. Based on the performance analysis, we proposed an adaptive design algorithm to select the best combination from a subset of frequencies that maximizes the detection performance. Our numerical examples showed that the sequential approach requires more coherent pulses to match the performance of the simultaneous usage of multiple carriers in OFDM format. We also studied the extent of performance degradation due to employing a subset of available frequencies.

2.3.4 Passive Radar for Target Detection

Problem Description
Much attention has been given to passive radar systems of late. Many signals have been analyzed and studied as possible illuminators of opportunity including Digital Audio Broadcast (DAB), Digital Video Broadcast (DVB), FM radio, cellphone base-stations, and various satellite systems.

Background
DVB-T digital television signals provide an especially attractive opportunity for radar, since they offer a powerful, well-defined signal with minimal cost to the radar user. The signal has sufficient bandwidth to provide reasonable precision in range and is noise-like allowing for good range compression and Doppler estimation.

Progress
We have provided a detailed overview of Digital Video Broadcasting Terrestrial (DVB-T) signal structure and the implications for passive radar systems that use these as illuminators of opportunity. In particular, we have analyzed the ambiguity function and made explicit its features in delay and Doppler in terms of the underlying structure of the DVB-T signal. Ambiguities are managed via the development of a set of mismatched filter weights that are applied to the reference signal prior to range-Doppler map formation. The development of the mismatched filter is based on previous work with an extended improvement for ambiguity peak reduction a wider variety of DVB-T signals.

This research was performed by Andrew Harms in collaboration with Linda Davis from the University of South Australia and James Palmer from the Defence Science and Technology Organisation, Adelaide, Australia [34]. The collaboration is the result of a summer internship at the University of South Australia.

2.4 Target Tracking

2.4.1 Monopulse MIMO Radar for Target Tracking

Problem Description
We considered target tracking by multi-input multi-output (MIMO) radar systems with widely separated antennas using monopulse processing at the receivers.

Background
MIMO radar systems with widely separated antennas help view the target from different angles, thereby providing spatially diverse looks. Monopulse based angle tracking systems are immune to pulse-to-pulse fluctuations as they perform simultaneous lobing.

Progress
We proposed a MIMO radar system with widely separated antennas that employs monopulse processing at each of the receivers [35], [36]. We used Capon beamforming to generate the two beams required for the monopulse processing. We also proposed an algorithm for tracking a moving target using this system. This algorithm is simple and practical to implement. It efficiently combines the information present in the local estimates of the receivers. Since most modern tracking radars already use monopulse processing at the receiver, the proposed system does not need much additional hardware to be put to use. We simulated a realistic radar-target scenario to demonstrate that the spatial diversity offered by the use of multiple widely separated antennas gives significant improvement in performance when compared to conventional SISO monopulse radar systems. We also showed that the proposed algorithm keeps track of rapidly maneuvering airborne and ground targets under hostile conditions like jamming.

2.4.2 Cognitive Radar for Target Tracking in Multipath Scenarios

Problem Description
In [37], we addressed the problem of target tracking in a multipath environment using a cognitive radar.

Background
Radars operating in urban environments suffer from the interference of multipath reflections. The strength of the line-of-sight (LOS) component can be very weak and in some cases there may not be a LOS component due to the shadowing effect. A standard radar using only the LOS return for the tracking procedure may fail to provide an updated state estimate in such cases. Therefore, to obtain an improved estimate of the target state, the radar should be capable of exploiting the information in the non-LOS (NLOS) radar returns, thereby providing spatial diversity. Cognitive radar is a new idea in the radar community. A cognitive radar uses the feedback provided by the interactions with the environment to continuously adapt to the environment and optimize the waveforms based on the feedback, thereby providing waveform diversity.

In [37], we proposed a cognitive radar system that combines the advantages of waveform diversity and spatial diversity for target tracking.

Progress
In [37], we considered the received signal to be a linear combination of delayed and Doppler shifted versions of the transmitted signal. We employed wideband signaling so that various multipaths on the received signal are resolvable. At the receiver, we coherently combined the delayed versions of signals received on each path to construct a new measurement vector. To separate the signals, we need the estimates of the delays and the attenuations corresponding to each path, which were obtained by solving a sparse reconstruction algorithm. We then performed sequential Bayesian filtering using a particle filter and waveform optimization to minimize the predicted Posterior Cramér Rao Bound in the next pulse repetition interval.

2.4.3 Sparsity-Based Multi-Target Tracking Using OFDM Radar

Problem Description
In [38], [39], we proposed a sparsity-based approach to track multiple targets in a region of interest using an orthogonal frequency division multiplexing (OFDM) radar.

Background
In a particular pulse interval, a multi-target scene is inherent sparse in the delay-Doppler plane, i.e., the targets lie only at a few points on the delay-Doppler plane. This enables us to efficiently track the targets by solving a simple sparse recovery algorithm through a linear program.

Progress
In [38], [39], we first presented a state model describing the dynamic behavior of the targets. Then, we developed a parametric measurement model considering an OFDM radar. Next, by exploiting the sparsity in the delay-Doppler plane, we convert the OFDM measurement model to an equivalent sparse measurement model, in which the non-zero components of the sparse vector correspond to the scattering coefficients of the targets. In our model, the sparse vector exhibited an additional structure in the form of the non-zero components appearing in clusters (blocks). Such vectors are referred to as block-sparse. In the tracking filter, we exploited this block-sparsity property in developing a block version of the compressive sampling

matching pursuit (CoSaMP) algorithm. We presented numerical examples to show the performance of our sparsity-based tracking approach and compared it with a particle filter (PF) based tracking procedure. The sparsity-based tracking algorithm took much less computational time and provided equivalent, and sometimes better, tracking performance than the PF-based tracking. By applying compressive sensing (CS) to our block-sparse model, we also found similar results even with a smaller number of measurements.

2.4.4 Urban Tracking with Waveform Design in High Clutter

Problem description
We integrated multipath exploitation with waveform design in urban radar for target tracking in [40]. Our main assumption in addressing this problem was that the targets were perfectly detected. However, in a realistic urban terrain scenario, there exist many multipath measurements with high uncertainty in their origin due to low signal-to-noise ratio (SNR) and high clutter. As a result, the probability of detection of the true target measurement is not one. We now consider the problem of tracking with waveform design in the urban environment with imperfect detections due to clutter.

Background
The received signal in urban environment operations bounces off multiple man-made objects before and after impinging on a target. These multipath signals may not include a response from the actual target directly as it is not present in its line-of-sight (LOS). The response may be just clutter, consisting of received echoes from stationary objects in the field of operation without the actual target. Incorporating the multipath returns as valid measurements in highly cluttered scenarios is a challenging problem as each subsequent bounce after the LOS bounce is expected to undergo loss in SNR and drastically affect the probability of detection. Also, as the target maneuvers, the types of bounces change due to the location of the buildings with respect to the target and the radar sensor, causing variation in the probability of detection. Data association is thus a crucial stage in tracking as it has to validate measurements for each of the arbitrary number of bounces and also dynamically adapt to the varying probabilities of detection in each region. Standard data association techniques, such as the use of the nearest neighbor standard filter, the optimal Bayesian data association filter or the probabilistic data association filter, have to be modified to include multiple path returns.

Progress
We propose a probabilistic data association approach where measurements corresponding to true target returns (through LOS) and virtual target returns (through non-LOS) are validated. The validated measurements are then fused such that they correspond to the common ground-moving target. An interactive multiple model probabilistic data association filter (IMM-PDAF) is designed for tracking the target incorporating varying detection probabilities due to the different types of returns. We then extend the tracking problem to include a technique for predicting the tracking mean-squared error (MSE), which incorporates the imperfect detection probabilities and transmission waveform parameters. The predicted tracking MSE is used as the cost function to adaptively choose the transmission waveform for the next time step. In [41]–[43], we demonstrate the proposed approach under different signal-to-clutter conditions. The integrated system, combining multipath data association and adaptive waveform design, was shown to increase the tracking performance and reduce the number of lost tracks. We tested our approach using a representative example of a challenging urban environment that DARPA used in their 2009 Multipath Exploitation Radar program.

2.4.5 Tracking Using Waveform Design for MIMO Urban Radar

Problem description
We investigated the problem of integrating a waveform agile multiple-input and multiple-output (MIMO) sensing system with multipath exploitation radar for tracking in urban terrain. Specifically, we considered MIMO radar with widely-separated transmitters and receivers, and demonstrate the improvement in tracking performance due to the optimal choice of transmitted waveform in each of the MIMO transmitters.

Background
One of the main advantages of MIMO sensing systems is the characteristic feature of being able to transmit a different waveform by each transmitter. Since we have obtained an increased tracking performance by integrating multipath exploitation and waveform design, we further expect to obtain additional performance improvements by incorporating MIMO systems into urban radar. A difficult problem when experimenting

with different urban terrain and radar configurations for tracking is the construction of multipath regions that describe the type of returns with each new region for use in the measurement equations. This is especially challenging for a given MIMO radar configuration and an urban map, since we need to first mark the possible bounces as individually seen by each transmitter and receiver. The regions corresponding to any transmitter-receiver pair can then be found by merging these individual maps. The measurements obtained as a combination of returns at each receiver can then be used for tracking and waveform selection.

Progress
We considered a MIMO radar configuration for which we constructed the multipath regions such that the shadow regions were completely eliminated due to the optimal placement of the transmitters and receivers. For this MIMO configuration, we also derived an optimal waveform design algorithm to track a moving target. The algorithm adaptively selects the waveform parameters for each tansmitter by minimizing the predicted mean-squared tracking error at each time step. Our simulations for the representative DARPA example showed improvements in tracking performance with the designed algorithm using a two-transmitter and two-receiver system when compared to a single collocated transmitter and receiver system [42]–[44]. Note that since all the shadow regions are eliminated using the MIMO system, there are no regions where the tracking progresses only based on the state predictions, unlike the case of the single collocated transceiver. Thus, optimal placement of the transmitters and receivers is necessary to achieve maximum performance gains.

2.4.6 Track-Before-Detect Multipath Exploitation Radar

Problem description
An urban environment is cluttered with buildings, trees, moving cars, and many other scatterers, resulting in low SNR and signal-to-clutter ratio (SCR) values. The transmitted signals and echo returns propagate over different paths before and after reaching the target, thus resulting in a very complex target detection problem. We consider increasing detection performance by integrating multipath exploitation with the track-before-detect (TBD) approach.

Background
In urban terrain, clutter is very high and the dense environment can decrease the observability of a target, causing very low SNR and SCR values. One method to increase target detection is by exploiting the multiple path returns. We have also tried to adaptively design the transmitted waveform so that detection performance could be improved. The idea was to select the transmit waveform from a library of waveforms in order to maximize the generalized likelihood ratio test (GLRT) statistic [45]. However, because of the multiple paths in the formulation of the returned signal, the received signal could not be just combined with the transmitted waveform to maximize the GLRT. Especially due to the low SNR, when traditional detection approaches cannot be used to detect a weak target, TBD methods can be used to track the target by integrating the low SNR sensor measurements over time. Specifically, using TBD, a low SNR signal can be tracked before declaring that a target is present so that no information is lost during detection.

Progress
We are developing a track-before-detect algorithm to track a moving target in an urban terrain environment using the available low SNR sensor measurements, the constructed multipath geometry regions, the corresponding nonlinear state space formulations, and the interactive multiple model particle filter to represent various motion models. Depending on the TBD performance for various SNRs, we will consider its integration with waveform selection methodologies.

2.5 Compressive Sensing for DOA Estimation and Radar

2.5.1 Compressive Sensing for MIMO Radar with Widely Separated Antennas

Problem Description
In [46]–[48], we addressed the problem of target estimation for multiple-input multiple-output (MIMO) radar systems with widely separated antennas using sparse modeling and compressive sensing.

Background

MIMO radar systems with widely separated antennas enable viewing the target from different angles, thereby providing spatial diversity gain. Compressive sensing allows us to accurately reconstruct data from significantly fewer samples than the Nyquist rate if the received signal is sparse in some basis representation. With the improvement in the capabilities of the computational resources, it has become more feasible to use compressive sensing for different medical and engineering applications.

Progress

We proposed a novel approach to accurately estimate properties (position, velocity) of multiple targets using distributed MIMO radar systems by employing sparse modeling [46]–[48]. We also introduced a new metric to analyze the performance of the radar system. We proposed an adaptive mechanism for optimal energy allocation at the different transmit antennas. We showed that this adaptive energy allocation mechanism significantly improves in performance over MIMO radar systems that transmit fixed equal energy across all the antennas. Further, we showed the improvement in performance over conventional single input single output (SISO) radar systems due to the spatial diversity offered by MIMO radar. We also demonstrated that the sampling rates can be significantly reduced by using compressive sensing at the receivers.

2.5.2 Electromagnetic Imaging Using Compressive Sensing

Problem Description

We proposed a novel method for localizing targets buried inside dielectric bodies based on the compressive sensing (CS) and the electromagnetic integral equation (EFIE) [49], [50]. The detection of buried targets is a complex inverse electromagnetic problem with wide range of applications such as biomedical imaging, nondestructive testing, subsurface probing, etc. The inverse electromagnetic problems are intrinsically ill-posed. The uniqueness of the solution is provided by using the regularization techniques. The constraints are chosen based on some a priori information about the solution. In this work, we exploited the assumption that the targets are sparse.

Background

The CS was successfully applied for estimating point targets in vacuum. The sparseness constraint produced high-quality images with superior resolution in comparison to the images computed by the standard DOA techniques such as beamforming. The application of CS was further extended to the subsurface and through-the-wall imaging. However, the proposed models used far-field assumption which is not valid in most of the inverse scattering problems.

Progress

We proposed a method for solving a two-dimensional (2D) inverse electromagnetic problem using the CS framework. We derived a linear near-field measurement model by means of the equivalence theorem and the electric field integral equation. We also studied the (3D) imaging method using the CS and the far-field measurements. We exploited the prior knowledge that the targets are sparse to solve these ill-posed problems. We demonstrated that the resolution of the images obtained using the near-field CS has superior resolution with respect to the images computed by beamforming or far-field CS. In the future work, we will numerically assess the performance of the imaging by computing the expected resolution versus detection parameters. We will also extend our work to the general, polarization sensitive, three-dimensional (3D) case.

2.5.3 Computable Quantification of the Stability of Sparse Signal Reconstruction

Problem Description

We investigated the stability of sparse signal reconstruction using the ℓ_1-constrained minimal singular value (ℓ_1-CMSV) of the measurement matrix [51], [52]. We showed that the ℓ_1-CMSV of the measurement matrix determines, in a very concise manner, the reconstruction performance of convex relaxation algorithms, such as the Basis Pursuit, the Dantzig selector, and the LASSO estimator. Numerical simulations illustrated that bounds based on the ℓ_1-CMSVs are tighter, and apply to sensing matrices/operators with a wider range of sizes. We showed also that, with high probability, many important random sensing matrices have ℓ_1-CMSVs concentrated around one, as long as the number of measurements is relatively large. We designed three algorithms based on the projected gradient method and the interior point algorithm to compute the ℓ_1-CMSVs of arbitrary measurement matrix. A lower bound of the ℓ_1-CMSV is also available by solving a semidefinite programming problem obtained via the lifting procedure.

Background
The last decade witnessed a burgeoning interest in exploiting the sparsity of signals in reconstruction. Applications include signal sampling and compression, medical imaging, solving electromagnetic inverse problems, control systems, commercial data mining, sensor networks, video information retrieval, to name a few. Our results are useful for determining the goodness of a sensing scheme before actually taking measurements, quantifying the confidence of a reconstructed signal, and serving as a basis for optimal sensing system design.

Progress
We are currently designing more efficient algorithms to compute ℓ_1-CMSVs. Promising directions are Rayleigh quotient minimization algorithms, first-order semidefinite programming, and augmented Lagrangian method. We are also combining other physical constraints to optimally design sensing matrices. Potential application areas include optimal $k-$space trajectory design for MRI and optimal waveform design for radar system.

2.5.4 Stability of Low-rank Matrix Reconstruction

Problem Description
We analyzed the stability of low-rank matrix reconstruction using the ℓ_*-constrained minimal singular value (ℓ_*-CMSV) of the measurement operator [53], [54]. We showed that the ℓ_*-CMSV determines the recovery performance of nuclear norm minimization based algorithms. Compared with the stability results using the matrix restricted isometry constant, the performance bounds established using the ℓ_*-CMSV are more concise and tight, and their derivations are less complex. The computationally amenable ℓ_*-CMSV and its associated error bounds also have more transparent relation with the measurement gain. We showed that several random measurement ensembles have the ℓ_*-CMSVs bounded away from zero with high probability, as long as the number of measurements is relatively large. These results are parallel to our results for stability analysis for sparse signal reconstruction, but the techniques employed are different.

Background
Many signal processing problems of practical importance can be reduced to the reconstruction of low-rank matrices, for example, collaborative filtering, linear system realization, face recognition, Euclidean embedding, and so on. Several considerations motivate the study of the stability of low-rank matrix reconstruction. First, for repeated sensing system, it is desirable to know the goodness of the measurement operator before taking measurements. Second, a stability analysis would offer a means to quantify the confidence in the reconstructed signal, especially when there is no other ways to justify the correctness of the reconstructed signal. Last but not least, in some applications we have the freedom to design the measurement operator by selecting the best one from a certain collection, which requires a precise quantification of the goodness of any given operator.

Progress
The applications that motivate our analysis of the stability for low-rank matrix reconstruction require the computation of the ℓ_*-CMSV. We are designing algorithms to compute the ℓ_*-CMSV and the associated error bounds. We plan to use these algorithms to compare the performance of different measurement operators in, for example, collaborative filtering and sensor network localization.

2.6 RF Tomography

2.6.1 Underground Void Detection

Problem Description
The problem of underground void detection is paramount to secure borders, sensitive areas, and for search and rescue missions.

Background
To date, no underground imaging technique emerged as a standard for close-in sensing of wide denied areas, where minimal human intervention is required. In 2007, Wicks proposed Radio frequency (RF) tomography to detect underground voids, such as tunnels or caches, over relatively wide areas of interest. The RF

tomography approach requires a set of low-cost transmitters and receivers arbitrarily deployed on the surface of the ground or slightly buried.

Progress
Using the principles of inverse scattering and diffraction tomography, we developed a simplified theory for below-ground imaging. We devised several inversion schemes based on arbitrarily deployed sensors and discussed limitations to performance and system considerations are discussed [55].

Then, we also developed three extensions to RF tomography, motivated by three challenges. One challenge is the lateral wave, which propagates in proximity of the air/earth interface and represents the predominant radiation mechanism for wide-area surveillance, sensing of denied terrain, or close-in sensing. A second challenge is the direct-path coupling between transmitters (Txs) and receivers (Rxs), that affects the measurements. A third challenge is the generation of clutter by the unknown distribution of anomalies embedded in the ground. These challenges are addressed and solved using the following strategies: 1) A forward model for RF tomography that accounts for lateral waves expressed in closed form (for fast computation); 2) a strategy that reduces the direct-path coupling between any TxRx pair; and 3) an improved inversion scheme that is robust with respect to noise, clutter, and high attenuation [56].

Experimental activities are also in progress to test RF tomography using scaled models in the anechoic room at UIC [57].

2.7 Other Published Work

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MURI: Adaptive Waveform Design for Full Spectral Dominance (2005-2010)

Key Topics of Last Two Years

Marker	Topic	Innovation and Challenge	Technology Potential
Robert Calderbank Princeton University	Local compressive detection and tracking	Conserve power and computational budgets without compromising performance	Detect and track targets based on local compressive sensing
Robert Calderbank Princeton University Bill Moran Stephen Howard Melbourne Univ. and DSTO, Australia	Instantaneous Radar Polarimetry	Baseline polarimetry is employed with great success in remote sensing and SAR but is serial and non-coherent making it less useful for detection and tracking	Makes the polarization scattering matrix available on a pulse to pulse basis at a computational cost comparable to single channel matched filtering
Robert Calderbank Princeton University Linda Davis UNISA, Australia James Palmer DSTO, Australia	Passive Radar Demonstration	The attraction of DVB-T digital television signals is that the signal has sufficient bandwidth to provide reasonable range estimation and is noise-like allowing good range compression and Doppler estimation	Demonstration that DVB-T digital television signals can be used as illuminators of opportunity
Mark Bell Purdue University	Biologically-inspired processing for enhanced delay-Doppler resolution	Use a processing approach mimicking echo locating bats	Significant increase in delay-Doppler resolution at a slight cost in terms of SNR
Mark Bell Purdue University	Frequency-coded waveforms for adaptive waveform radar	Design frequency-coded waveform sets for high delay-Doppler target resolution and discrimination	An adaptive waveform selection scheme allowing high resolution delay Doppler imaging
Arye Nehorai Washington University in St. Louis	Sparsity-based target estimation and tracking	Exploit delay-Doppler sparsity to improve the target estimation and tracking performance	Adaptive radar system using sparse modeling with reduced estimation times
Arye Nehorai Washington University in St. Louis	Target detection using MIMO radar	Model the clutter realistically using compound-Gaussian distribution	Adaptive MIMO radar system with improved detection performance

Arye Nehorai Washington University in St. Louis	Target detection in multipath scenarios	Exploit multipath components to improve the target detection performance	Adaptive OFDM radar that resolves and exploits the multipath propagations
Arye Nehorai Washington University in St. Louis	Polarimetric radar for target tracking	Realistically model the underlying physical phenomena and statistical characteristics	Sequential Monte Carlo based target tracking radar with polarimetric transceivers
Arye Nehorai Washington University in St. Louis	Biologically inspired coupled antenna array	Use antenna coupling filters inspired by the female Ormia ochracea	Active case: Improve the half-power beamwidth, sidelobe suppression, directivity of the radiation pattern Passive case: Enhance the resolution using smaller arrays
Arye Nehorai Washington University in St. Louis	Performance analysis for sparse support recovery	Analyze the performance of estimating the common support for jointly sparse signals based on their projections onto lower-dimensional space	Upper and lower bounds on the probability of error using the Chernoff bound and Fano's inequality, respectively
Arye Nehorai Washington University in St. Louis	Multi-objective optimization of OFDM radar waveform	Propose a constrained multi-objective optimization (MOO) based algorithm to optimally design the spectral parameters of the OFDM waveform	Adaptive OFDM waveform design to detect ground targets in urban environments
Danilo Erricolo University of Illinois at Chicago	RF Tomography	Exploit geometric diversity of illumination and observation in ground penetrating radar as well as operation at narrowband frequency	RF tomography system to image underground voids
Danilo Erricolo University of Illinois at Chicago	Propagation models for the electromagnetic field using ray based methods	Validate and exploit the Incremental Theory of Diffraction to achieve a novel incremental fringe formulation of Physical Optics	Improve accuracy of electromagnetic computations based on Physical Optics

Antonia Papandreou Suppappola Darryl Morrell Arizona State University	Waveform agile tracking and detection for different scenes	Develop detection and tracking algorithms for maneuvering targets in high clutter and with many multipath returns	Dynamic waveform selection in cluttered urban terrain scenes
Antonia Papandreou Suppappola Darryl Morrell Arizona State University	Multiple-input and multiple-output (MIMO) radar for target tracking	Exploit waveform design of multiple transmitters for target tracking and integrate with sensor scheduling	A waveform-agile MIMO radar system for tracking multiple targets for urban warfare
Navin Khaneja Harvard University	Radar waveforms by adaptive Radon transform	Enhance delay Doppler resolution by waveform diversity and processing	Radon transform based radar waveforms with mitigated ambiguity
John Benedetto University of Maryland	Phase-coded waveform design	Construct complex valued constant amplitude zero auto-correlation (CAZAC) sequences	CAZAC software
Michael Zoltowski Purdue University Robert Calderbank Princeton University	Matrix waveform design for MIMO-Radar	Unitary Matrix of uni-modular waveforms for MIMO-Radar enabling waveform diversity for high-time-resolution, with multi-PRI matched filtering effecting separation of superimposed returns	Enables simultaneous trans-mission of complementary waveforms from multiple antennas/apertures for high time-resolution with zero self-interference
Michael Zoltowski Purdue University Robert Calderbank Princeton University	Multi-PRI matched-filtering of comple-mentary waveforms in high Doppler	Auto-compensation of Doppler enabling use of Unitary Waveform Matrix designs in the presence of moderate to high Doppler	Enables use of complement-ary waveforms over multiple PRIs in MIMO-Radar for high-time-resolution in practical Doppler scenarios
Michael Zoltowski Purdue University	MIMO-OFDM wire-less communication	Unitary subband filtering over space and time enabling simple separation of superimposed OFDM waveforms in MIMO-OFDM	High-Speed MIMO-OFDM supporting rapid multimedia data transfer

MURI: Adaptive Waveform Design for Full Spectral Dominance (2005-2010)

Arye Nehorai (Team Leader)
Washington University in St. Louis

Antonia Papandreou-Suppappola and Darryl Morrell
Arizona State University

Navin Khaneja
Harvard University

Danilo Erricolo
University of Illinois at Chicago

John Benedetto
University of Maryland

William Moran
University of Melbourne

Robert Calderbank
Princeton University

Mark R. Bell and Mike Zoltowski
Purdue University

Harry Schmitt
Raytheon Missile Systems

Students, Plenaries, and Special Issues/Sessions:

Number of PhD students supported	45
Number of MS students supported	3
Number of US students put into science/engineering program	8
Number of plenary talks	16
Special issues in journals	3
Number of peer reviewed journal papers	80
Special sessions in conferences	20
Number of conference papers	150

Promotions:

- Robert Calderbank, Dean of the Natural Sciences, Duke University, since 2010.
- Arye Nehorai, Chair of the Preston M. Green Department of Electrical and Systems Engineering, Washington University in St. Louis, since 2006.
- Arye Nehorai, inaugural holder of the Eugene and Martha Lohman Professorship of Electrical Engineering, Washington University in St. Louis, since 2006.
- Navin Khaneja, Gordon Mckay Professorship of School of Engineering and Applied Sciences with tenure, Harvard University, since 2008.
- Michael Zoltowski, holder of Thomas J. and Wendy Engibous Professorship of Electrical and Computer Engineering, Purdue University, since 2008.
- Danilo Erricolo, received tenure in 2007.
- Antonia Papandreou Suppappola, promoted to full Professor in 2008.

Awards and Prizes:

- Robert Calderbank, member of the National Academy of Engineering, since 2005.
- John Benedetto, 2011 Wavelet Pioneer Award at the SPIE Defense, Security, and Sensing Conference.
- Arye Nehorai, 2006 Technical Achievement Award, IEEE Signal Processing Society.
- Arye Nehorai, 2009 Meritorious Service Award, IEEE Signal Processing Society.
- Navin Khaneja, 2005 Bessel prize, Humboldt foundation.
- Antonia Papandreou-Suppappola, 2008 IEEE Phoenix Section Chapter/Society Research Award for the SenSIP Center.
- Danilo Erricolo, 2006 UIC College of Engineering Gold Faculty Research Award.
- Danilo Erricolo, 2008 UIC College of Engineering Faculty Research Award.
- Stephen Howard (MURI collaorator), DSTO Fellowship, 2010-2012.

Student Awards

- Badria M. Elnour, 2006-2007 IEEE Antennas and Propagation Society Graduate Fellowship award. (Advisor: Danilo Erricolo)
- Murat Akcakaya, Best Student Paper Award (first place) at the *2010 Waveform Diversity & Design Conference*. (Co-author: Arye Nehorai)
- Murat Akcakaya, co-author, Best Student Paper Award (third place) at the *2010 IEEE International Radar Conference*. (Co-author: Arye Nehorai)
- Murat Akcakaya, Best Student Paper Award (third place) at the *2010 Asilomar Conference on Signals, Systems, and Computers*. (Co-author: Arye Nehorai)
- Satyabrata Sen, Best Student Paper Award (second place) at the *2010 Waveform Diversity & Design Conference*. (Co-author: Arye Nehorai)
- Lifeng Miao, Best Student Paper Award (first place) at the *2010 IEEE Workshop on Signal Processing Systems*. (Co-author: Antonia Papandreou Suppappola)
- Jun Jason Zhang, Best Student Paper Award (third place) at the *2009 Waveform Diversity & Design Conference*. (Co-author: Antonia Papandreou Suppappola)

Technology Transitions:

Originator	Transition Topic	Recipient
MURI Team	Adaptive waveform design for detecting low-grazing-angle and small-RCS targets	NRL
MURI Team	Waveform adaptivity for radar	AFRL, AFIT
Benedetto	CAZAC software	AFRL
Benedetto	Bjorck CAZAC ambiguity function constructions	Northrop-Grumman, MITRE
Calderbank, Howard and Moran	Instantaneous radar polarimetry	MITRE
Calderbank and Howard	Passive radar using DVB-T signals	DSTO
Howard and Moran	Adaptive radar testbed development	AFRL
Moran	Radar-on-a-chip project for automotive applications	Victorian State Government, Australia
Moran	Small portable weather radars	Australian research council discovery project
Erricolo	Radio frequency tomography	AFRL
Khaneja	RF pulse sequences/waveforms in magnetic resonance applications	TUM, Aarhus, Harvard Medical School, MIT
Nehorai	OFDM MIMO radar for low-grazing angle tracking	Raytheon
Nehorai	MIMO radar for target tracking	GTRI
	Adaptive polarimetric and	

Nehorai	OFDM radar	AFRL
Nehorai	Applying sparsity based algorithms to radar estimation and tracking	AFRL
Nehorai	Biologically inspired antenna array design	AFRL
Papandreou and Morrell	Waveform-agile tracking in urban terrain	Lockheed Martin
Papandreou	Waveform-agile design algorithms in multi-modal sensing applications	AFRL
Papandreou	Waveform-agile design algorithms in structural health management of aerospace systems applications	AFRL

Students who Joined National Laboratories:

- Dr. Sen (advisor: Arye Nehorai) is now Wigner Fellow with the Complex Systems Group in the Computer Science and Mathematics Division at the Oak Ridge National Laboratory, Oak Ridge, Tennessee.
- Dr. Lo Monte (advisor: Danilo Erricolo) is now employed by General Dynamics Information Technology to work as a contractor for the AFRL/Sensors Directorate, WPAFB, Dayton, Ohio.

Special Issues in Journals:

- "Adaptive Waveform Design for Agile Sensing and Communication," *IEEE Journal of Special Topics in Signal Processing,* Jun. 2007. (guest editors: A. Nehorai, F. Gini, M. Greco, A. Papandreou, M. Rangaswamy)
- "Waveform-Agile Sensing and Processing," *IEEE Signal Processing Magazine,* Jan. 2009. (guest editors: A. Papandreou, A. Nehorai, R. Calderbank)
- "Managing Complexity in Multiuser MIMO Systems," *IEEE Journal of Special Topics in Signal Processing,* Dec. 2009. (guest editors: G. Matz, R. Calderbank, C. Mecklenbrauker, A. Naquib, E. Viterbo)